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(54) **MICRO ENVIRONMENTAL SENSING DEVICE**

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H01H 35/02 (2006.01)

(52) **U.S. Cl.** .... **200/61.45 R**; 200/61.45 M

(58) **Field of Classification Search** .... 200/61.49, 200/61.53, 61.45 R–61.45 M; 73/514.01, 73/514.16, 488, 514.21–514.24, 514.31, 73/514.34–514.36, 514.38
See application file for complete search history.

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Primary Examiner—Michael Friedhofer
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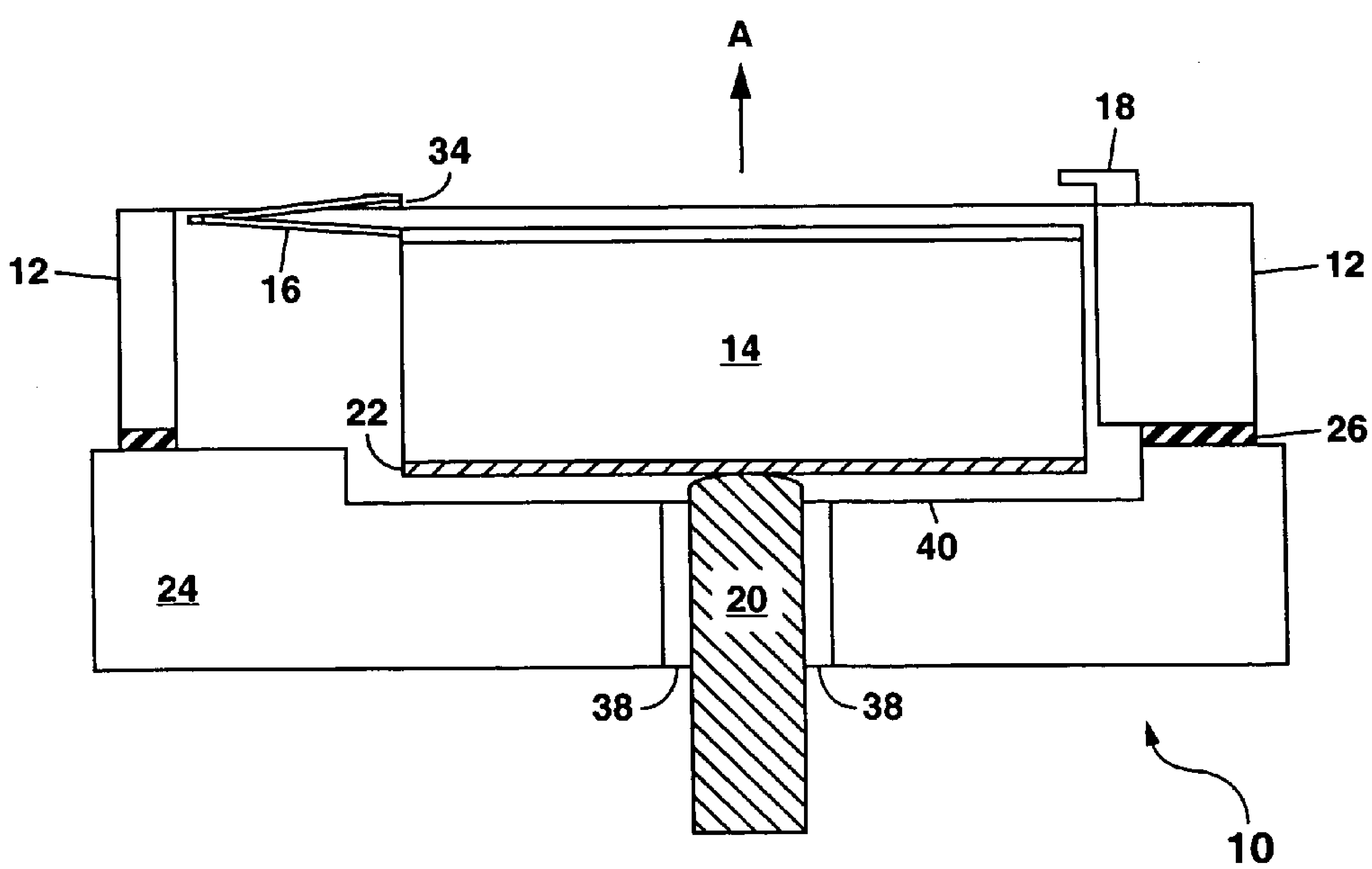
(57) **ABSTRACT**

A microelectromechanical (MEM) acceleration switch is disclosed which includes a proof mass flexibly connected to a substrate, with the proof mass being moveable in a direction substantially perpendicular to the substrate in response to a sensed acceleration. An electrode on the proof mass contacts one or more electrodes located below the proof mass to provide a switch closure in response to the sensed acceleration. Electrical latching of the switch in the closed position is possible with an optional latching electrode. The MEM acceleration switch, which has applications for use as an environmental sensing device, can be fabricated using micromachining.

35 Claims, 12 Drawing Sheets



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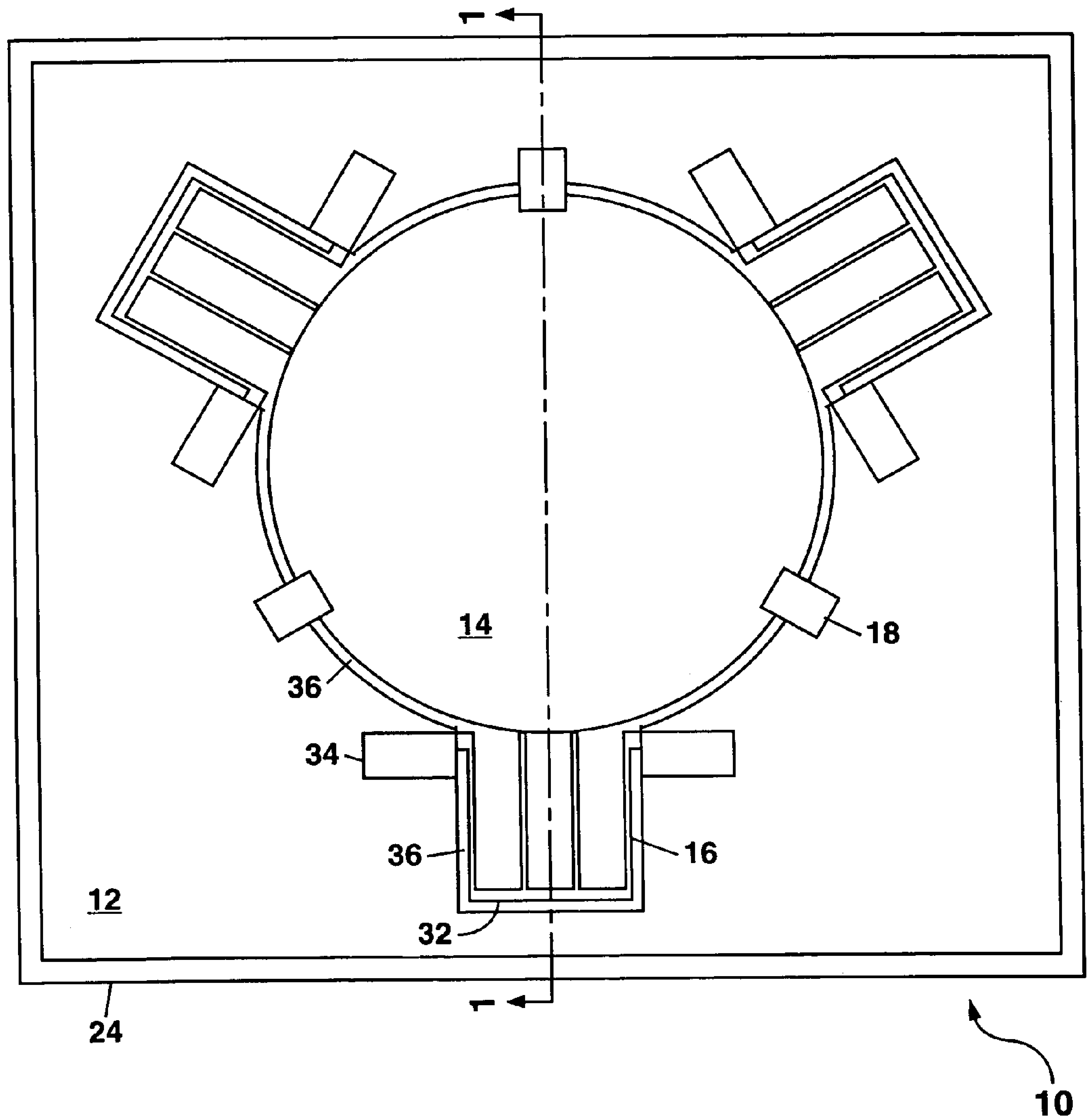

FIG. 1

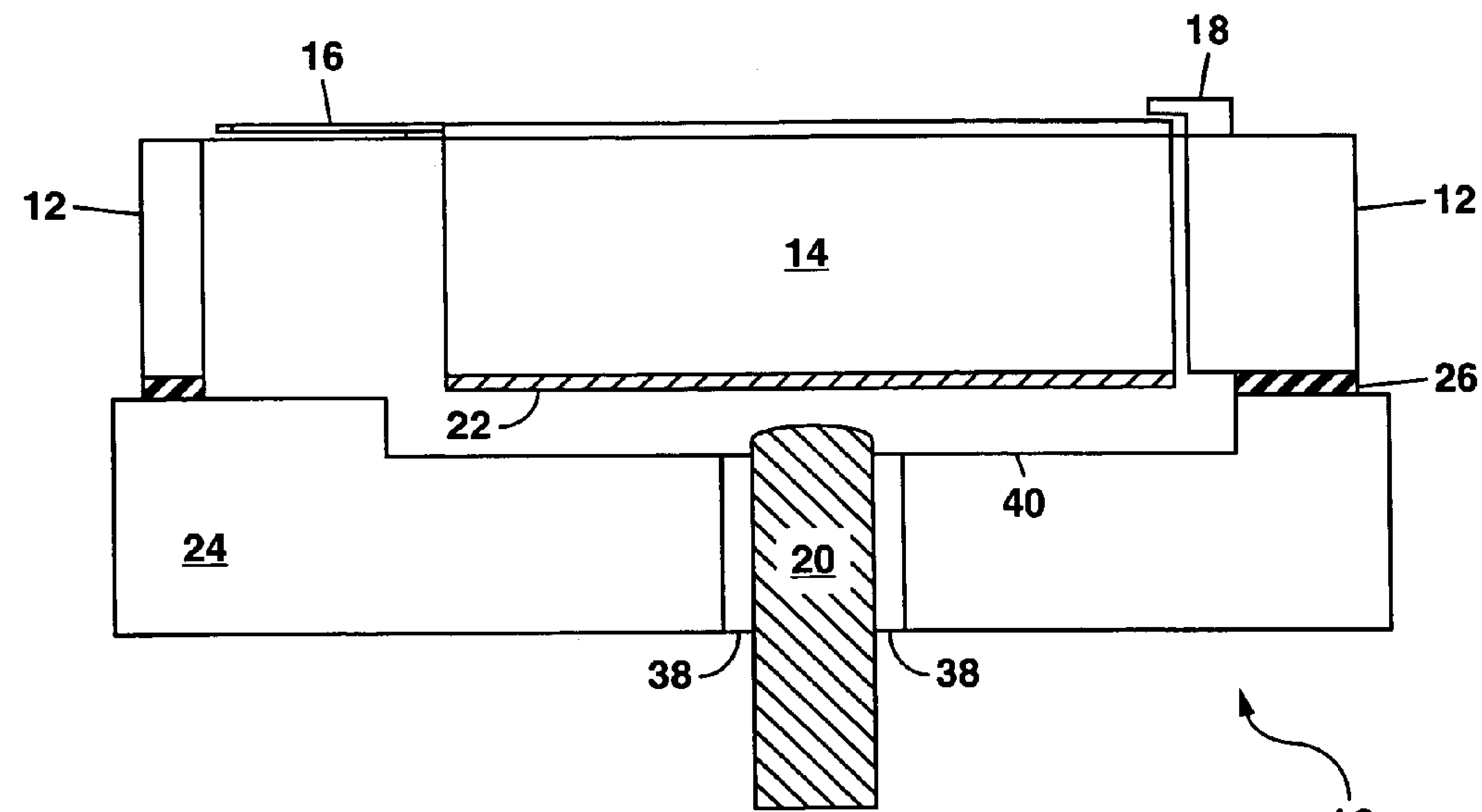
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FIG. 2A

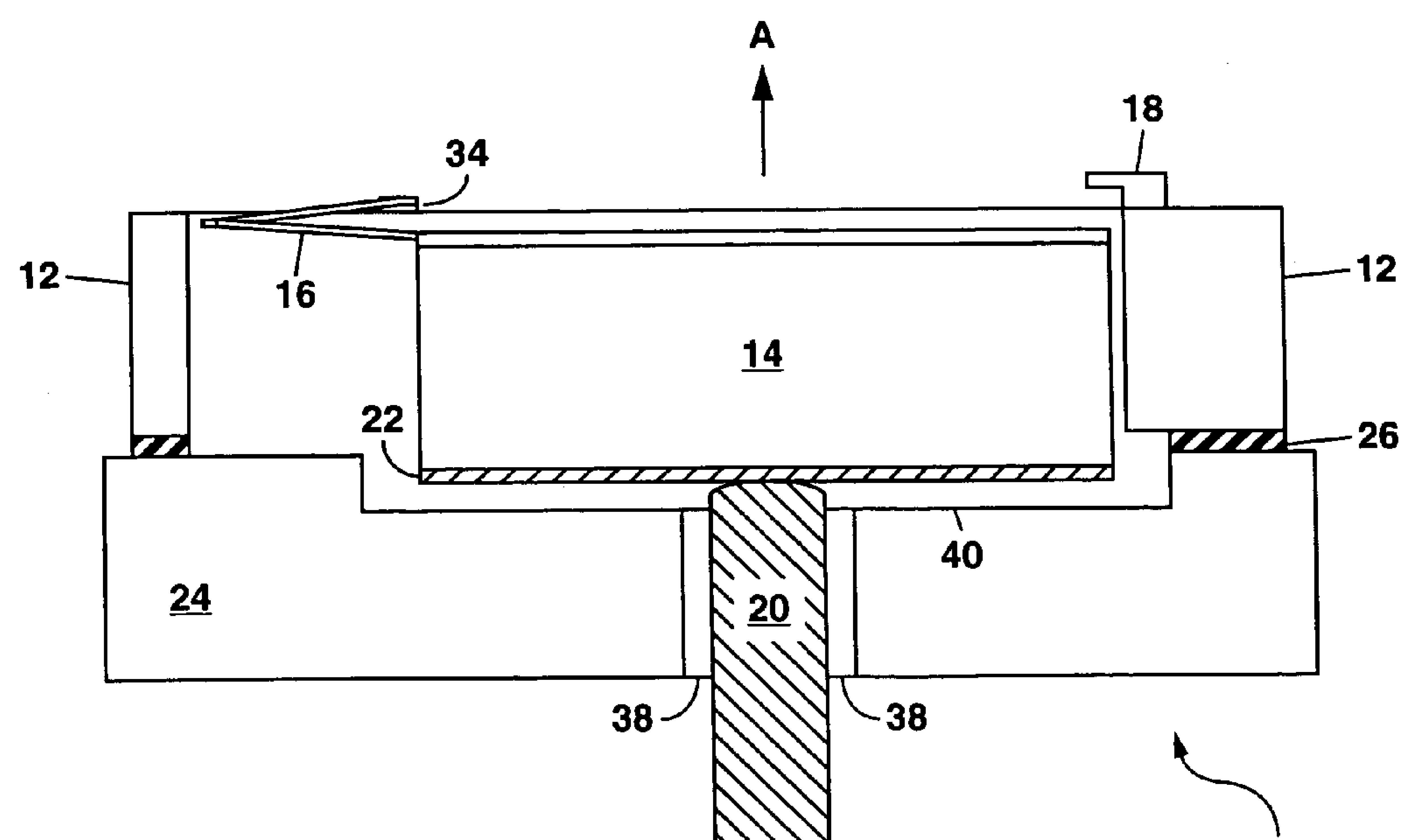
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FIG. 2B

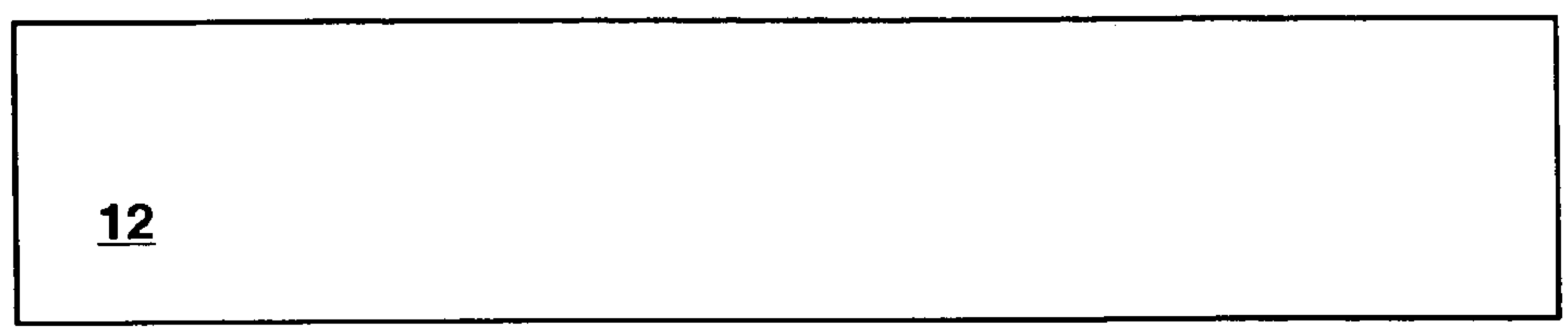

FIG. 3A

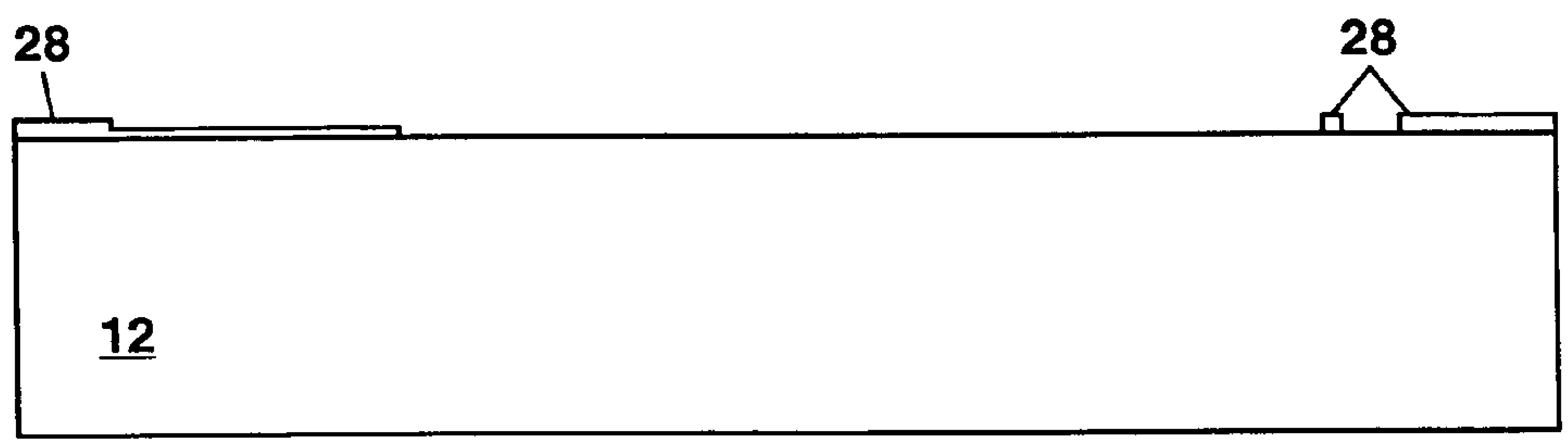

FIG. 3B

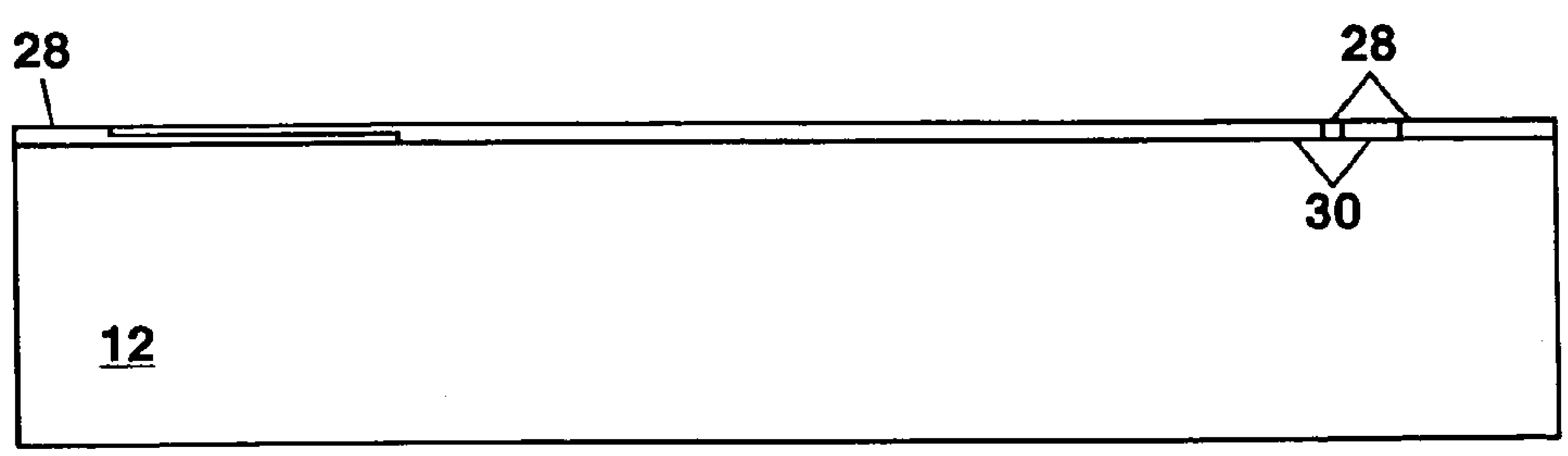

FIG. 3C

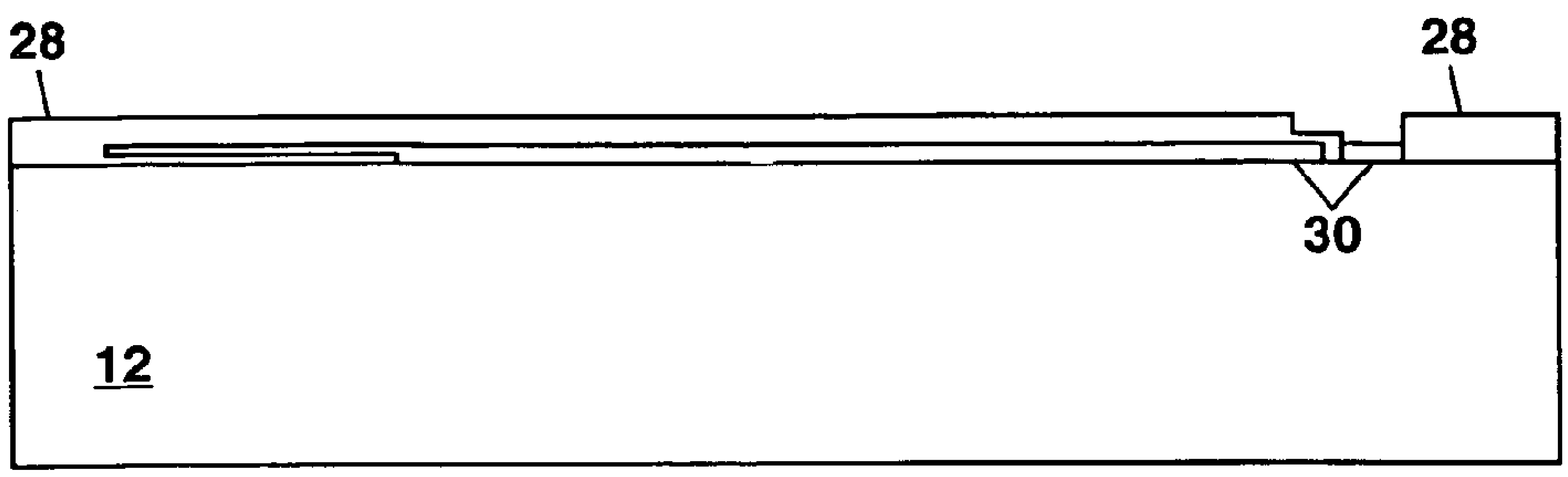

FIG. 3D

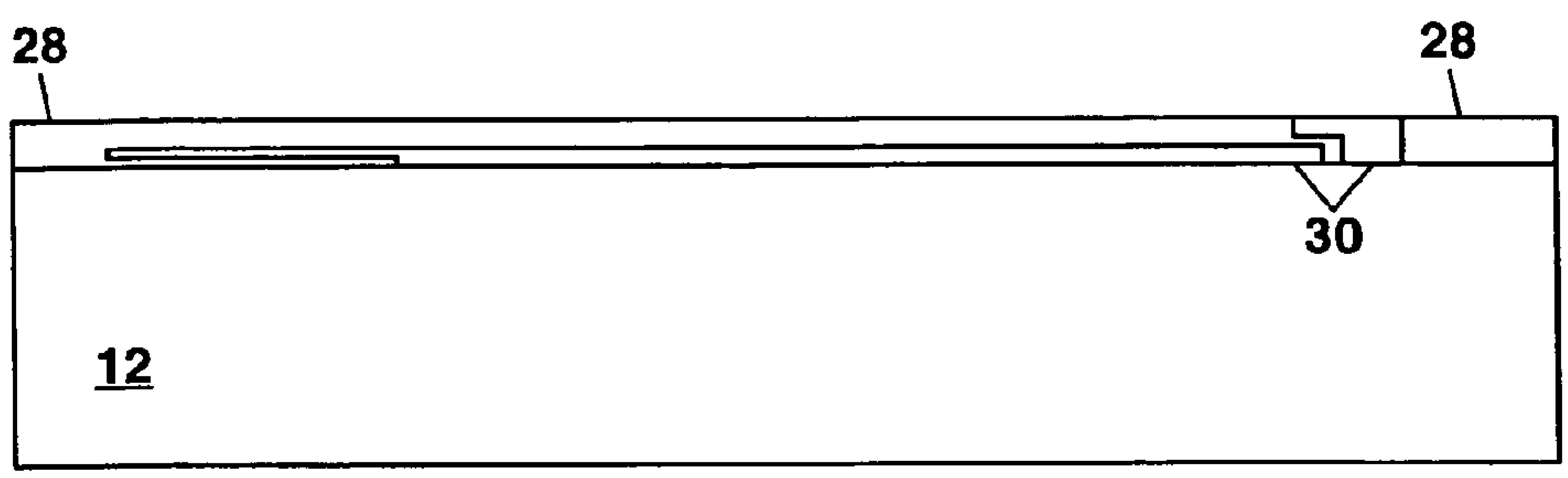

FIG. 3E

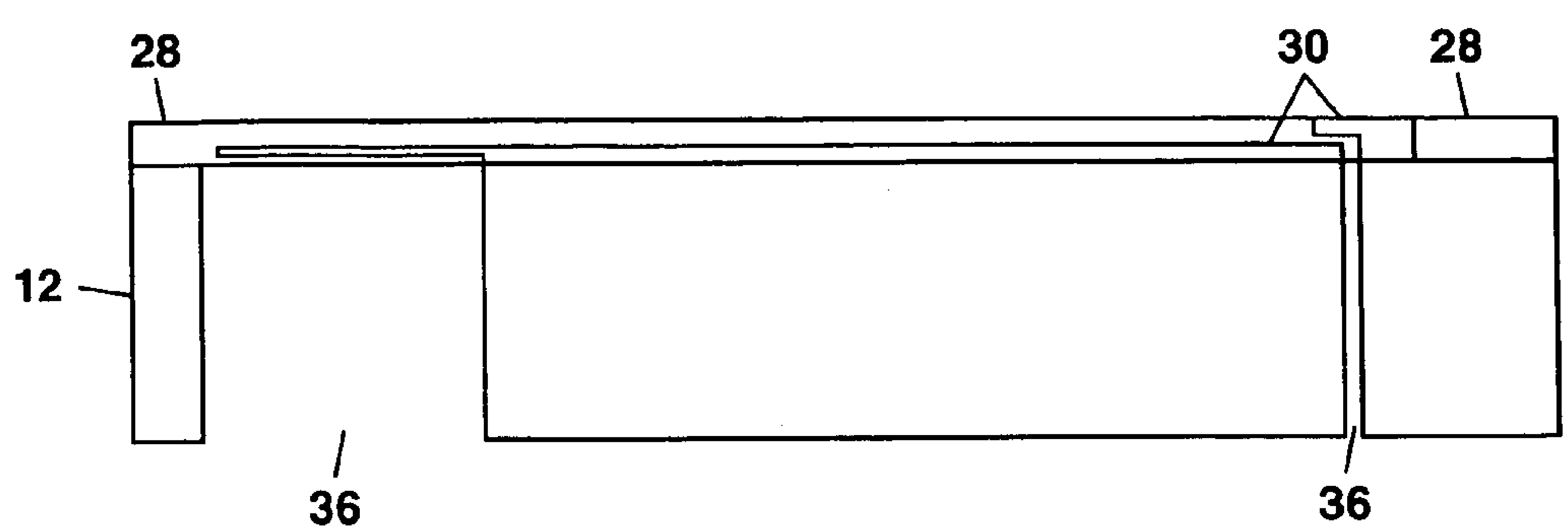

FIG. 3F

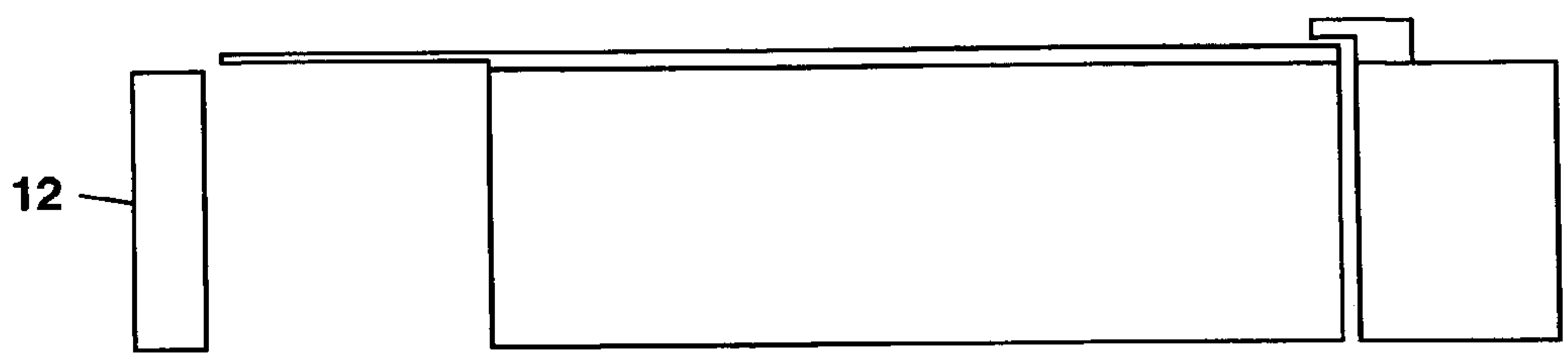

FIG. 3G

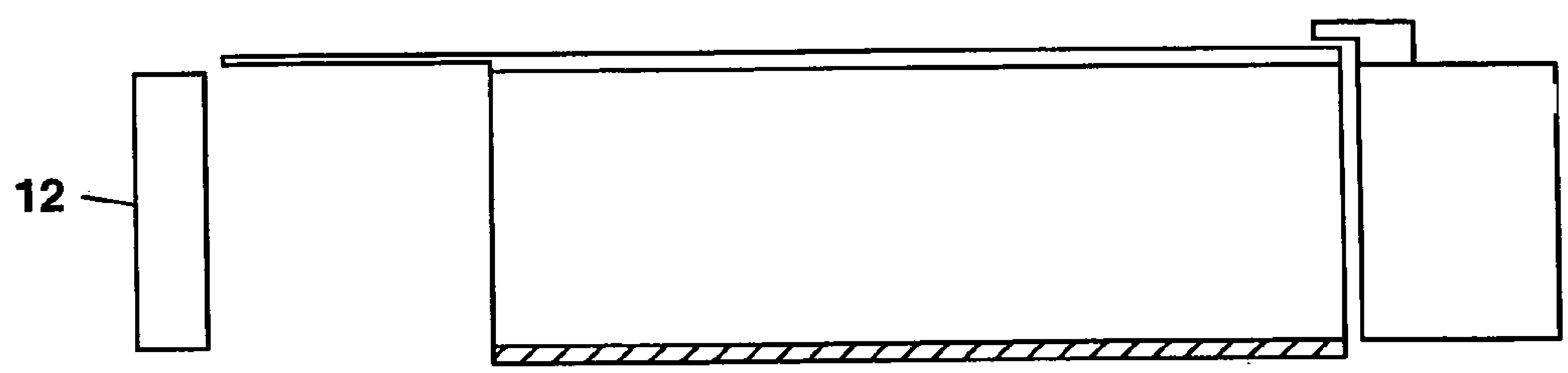

FIG. 3H

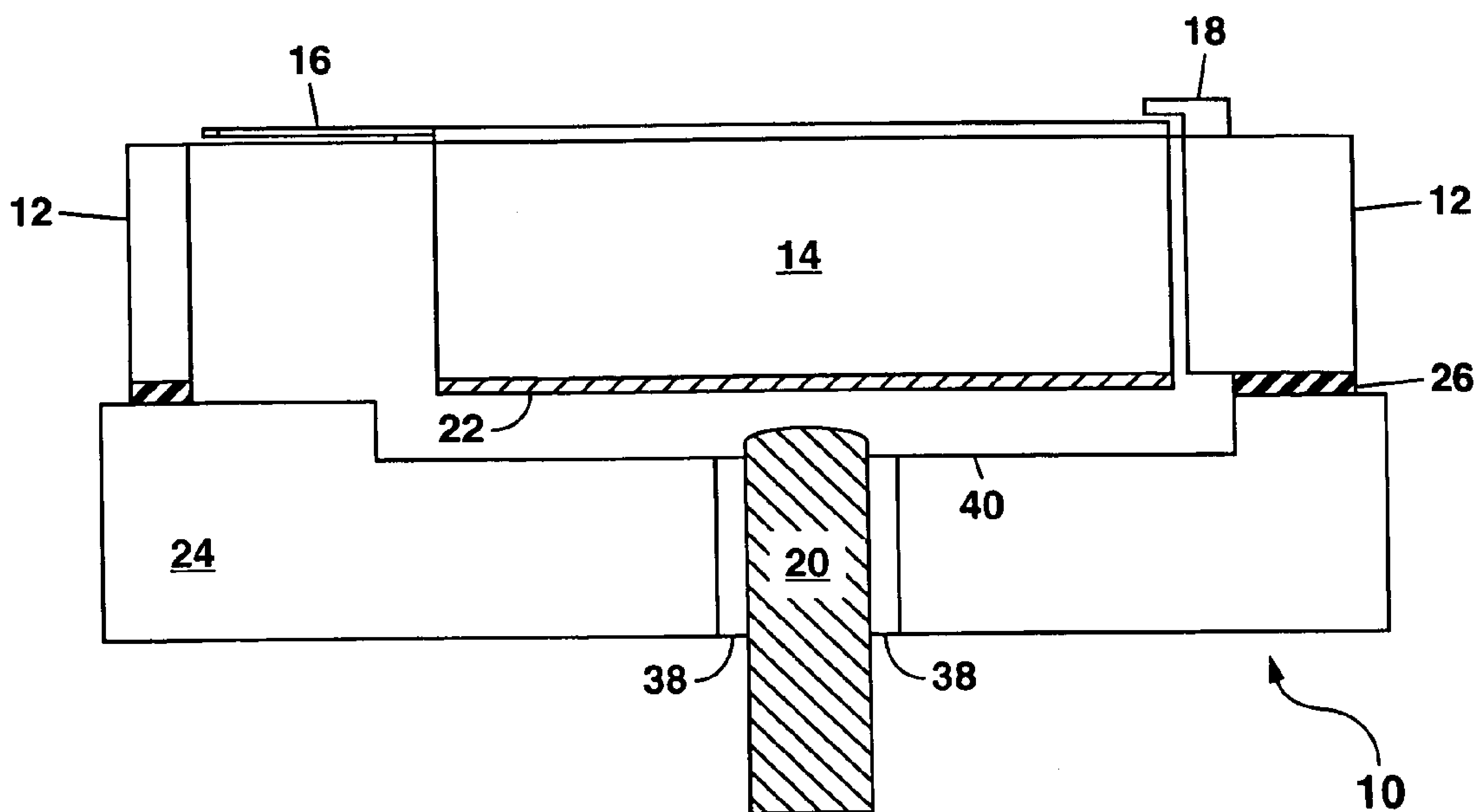

FIG. 3I

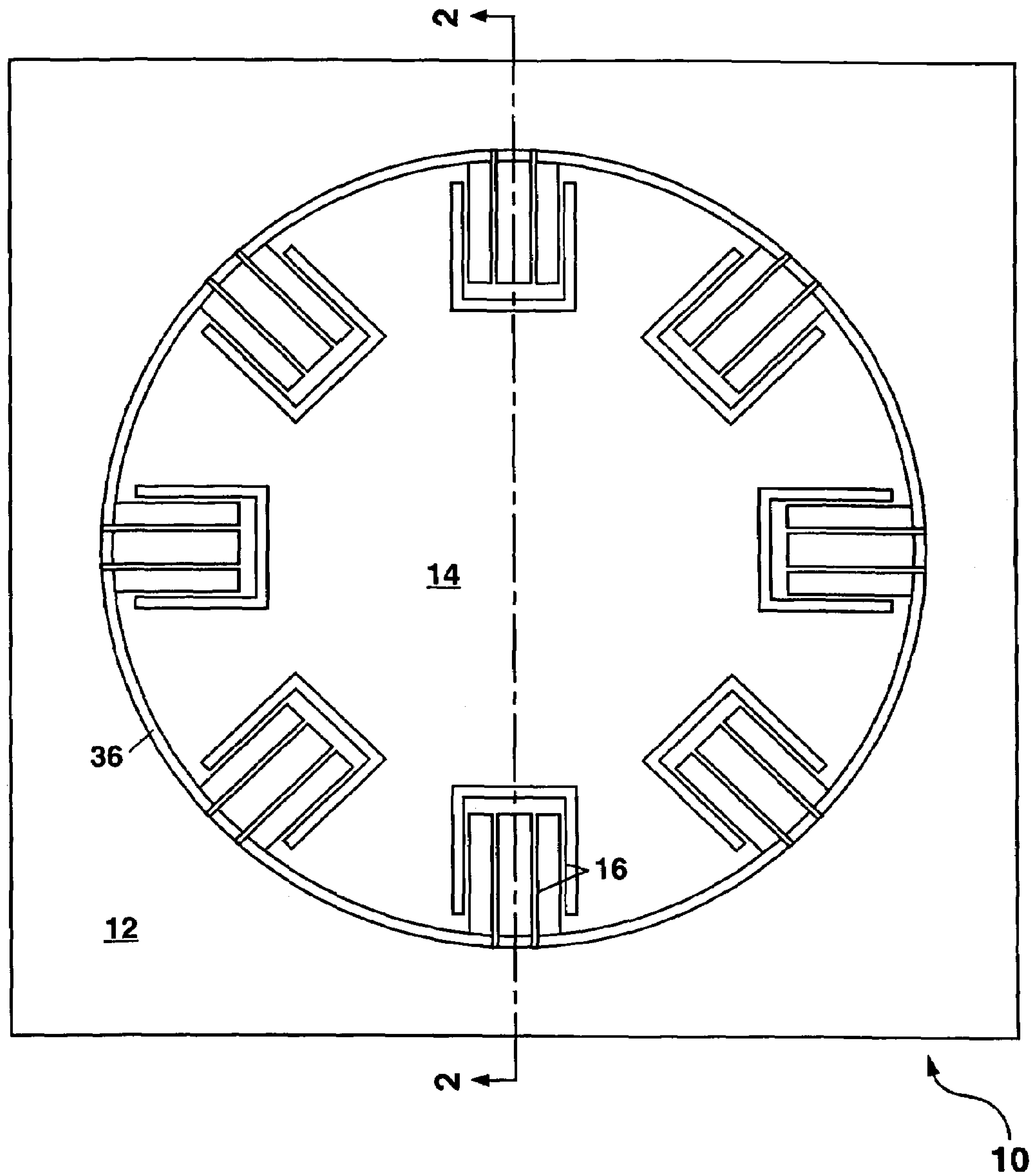

FIG. 4

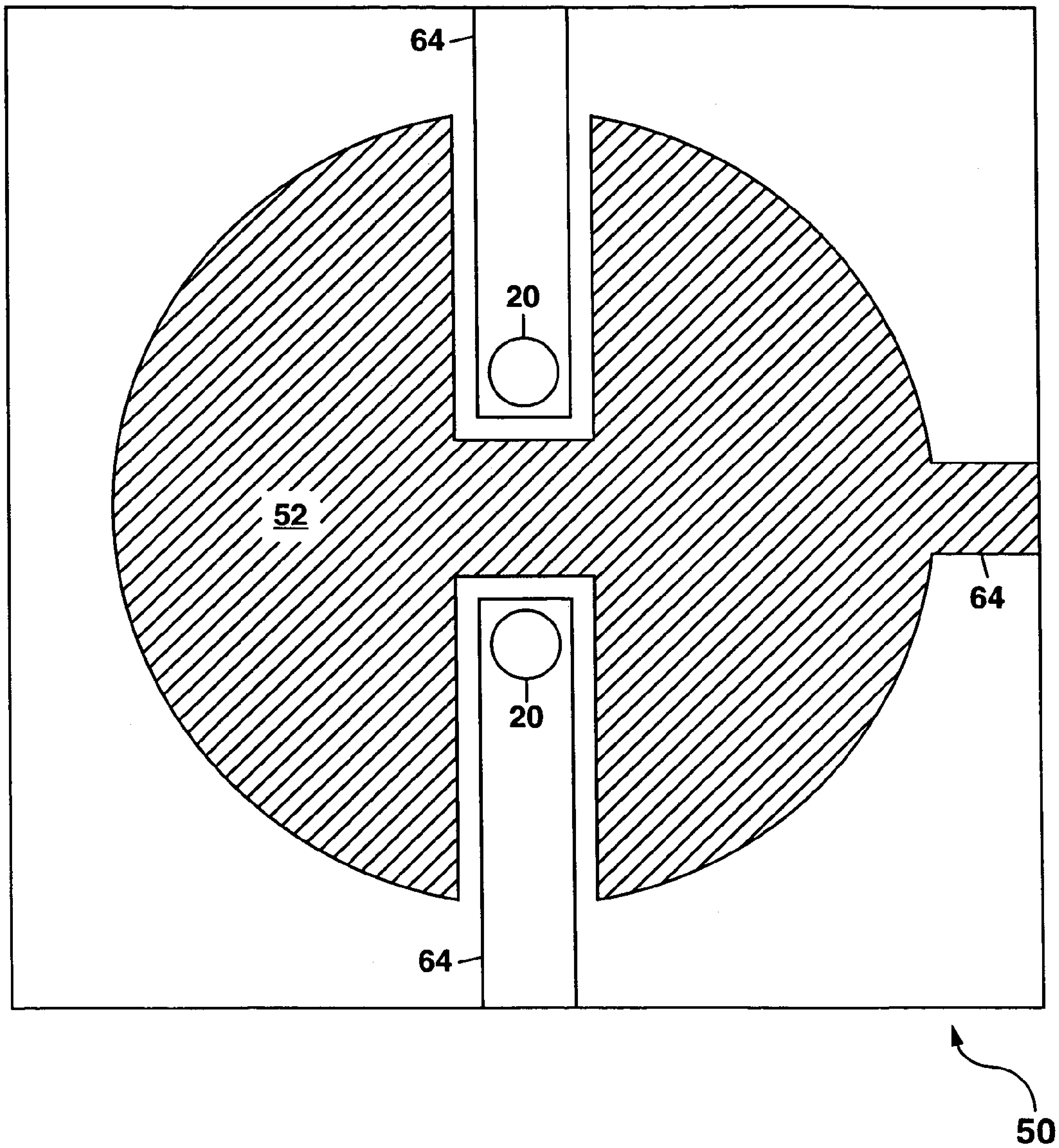

FIG. 5

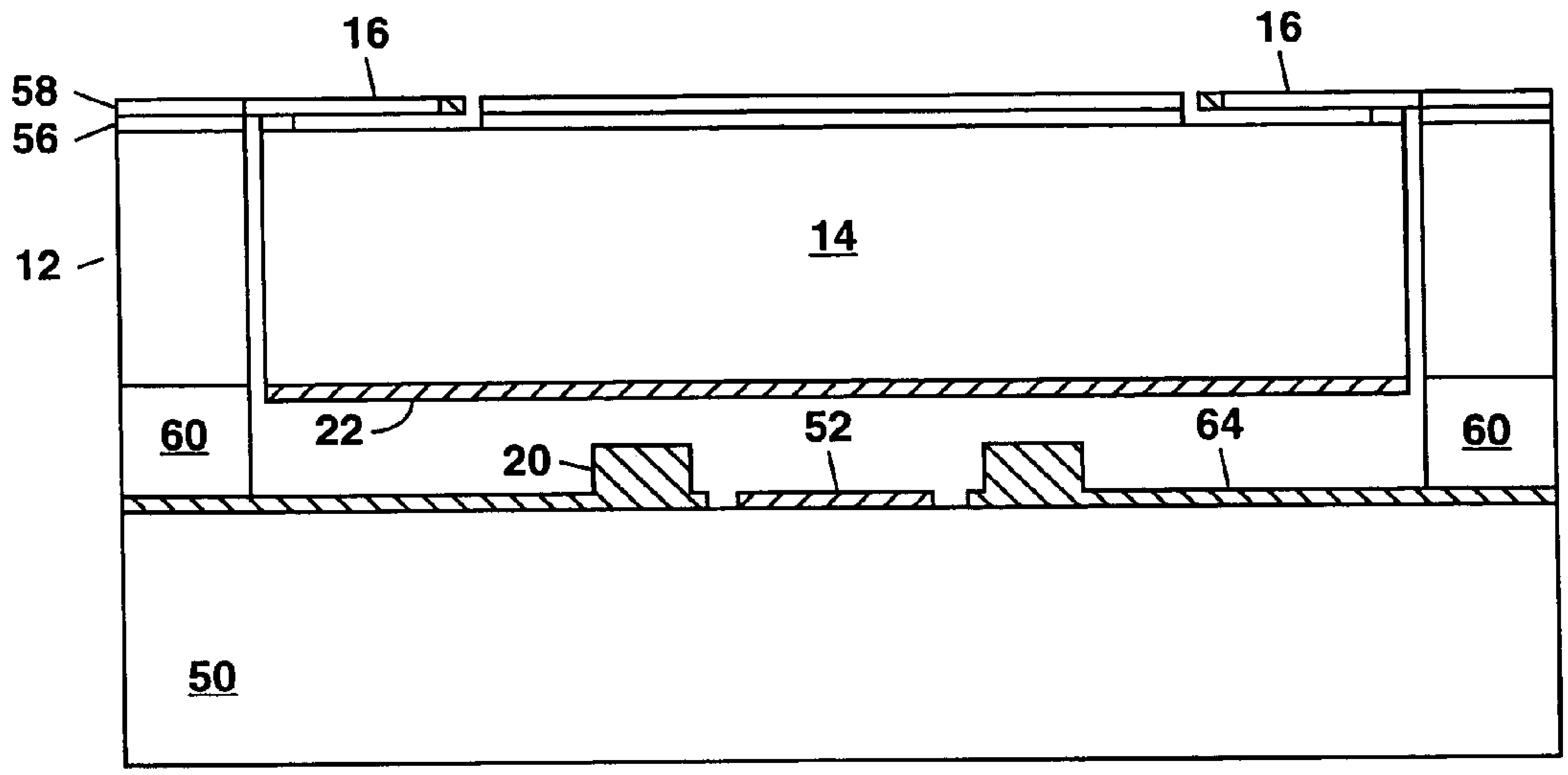
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FIG. 6A

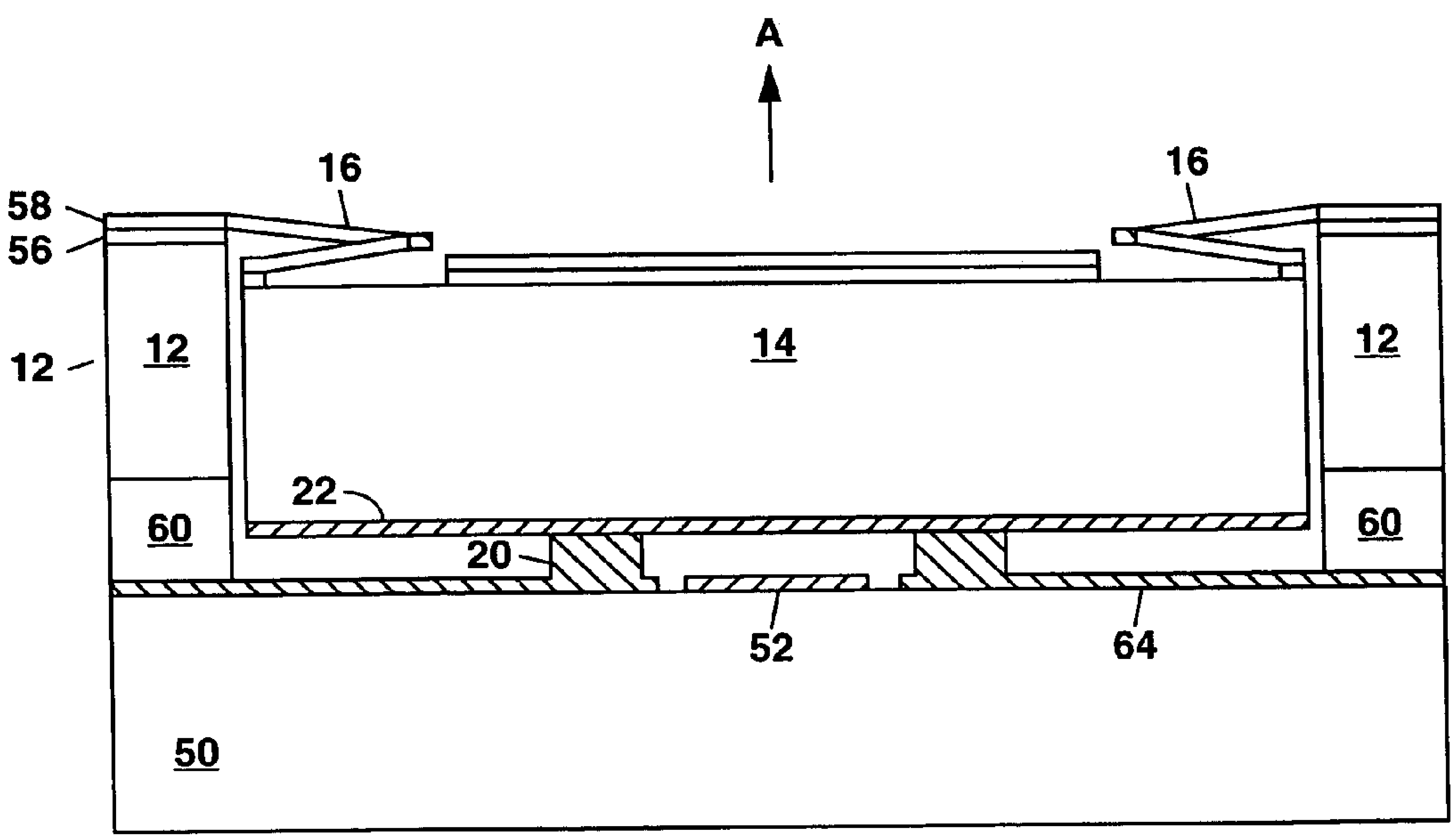
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FIG. 6B

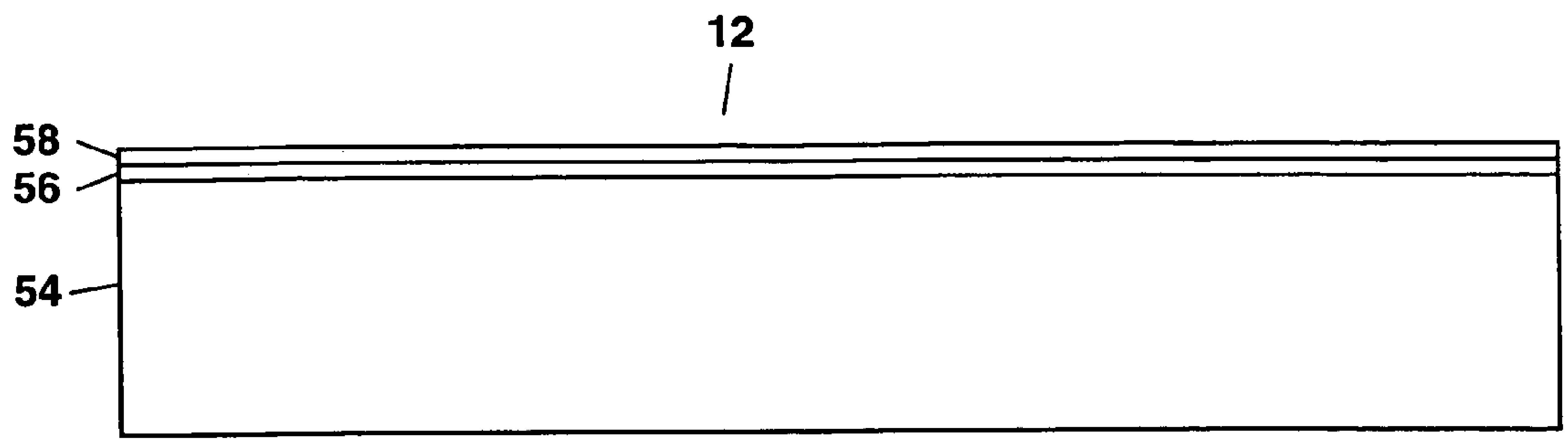

FIG. 7A

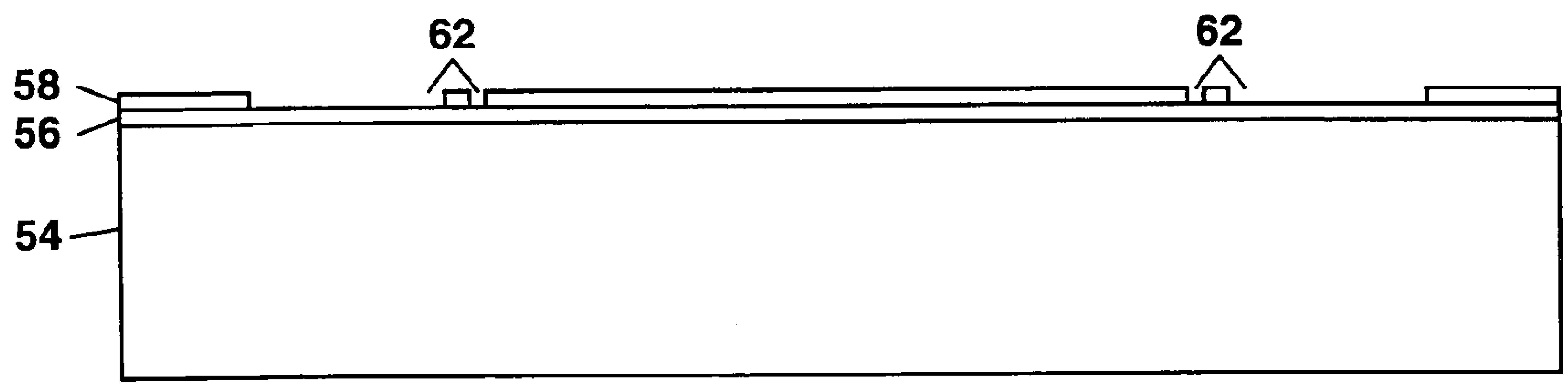

FIG. 7B

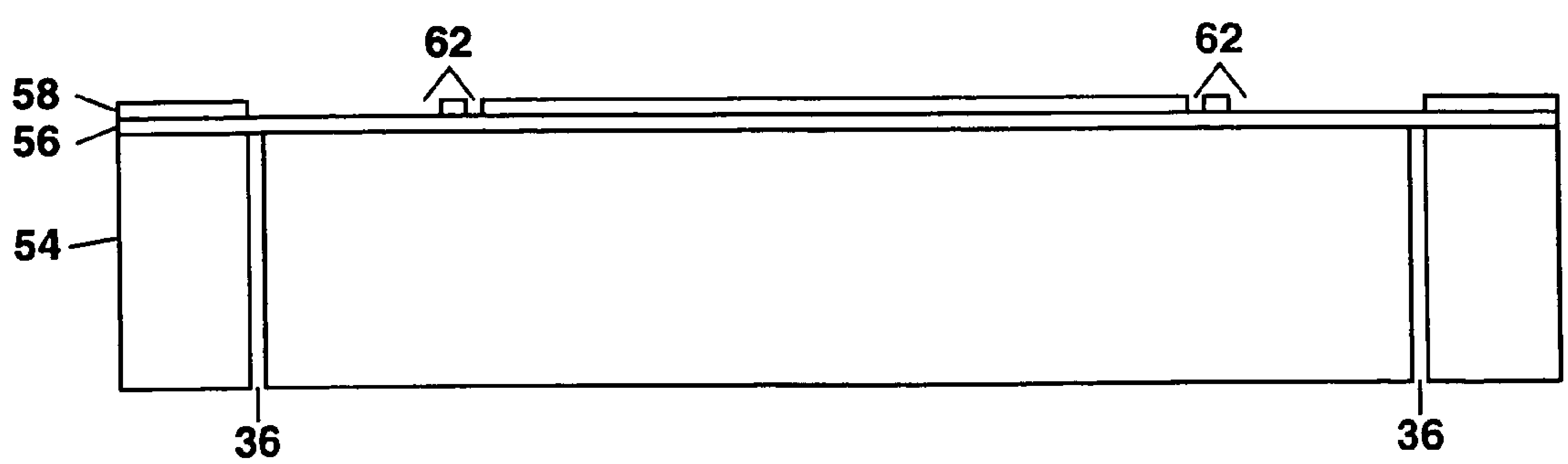

FIG. 7C

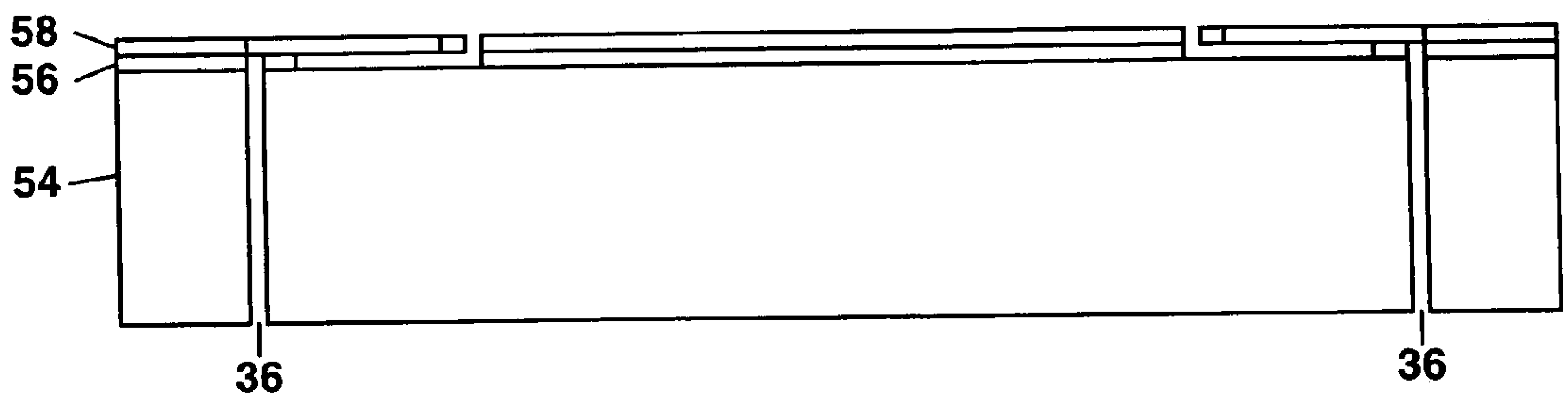

FIG. 7D

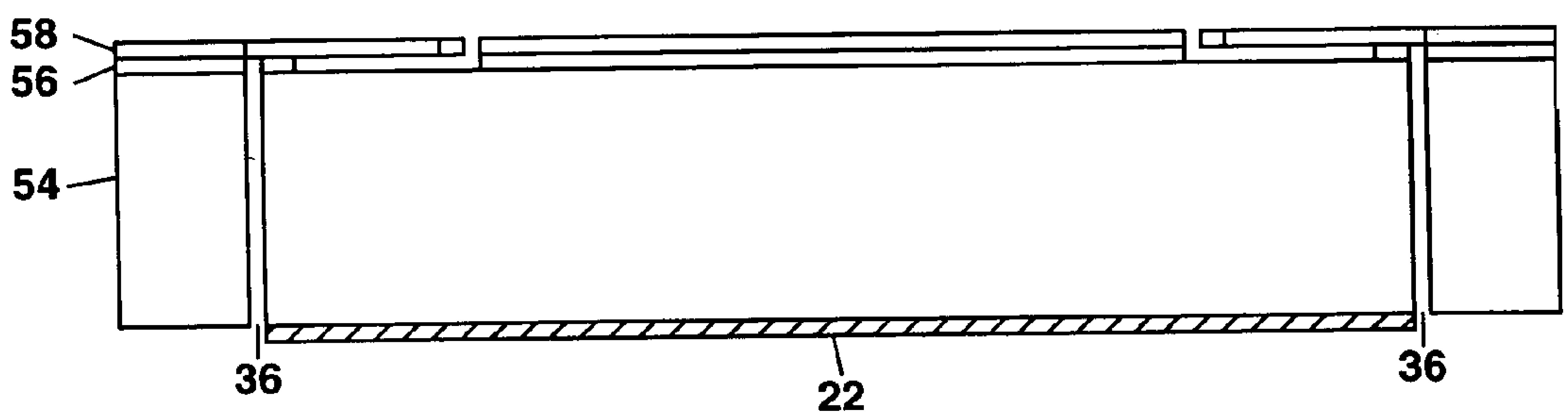

FIG. 7E

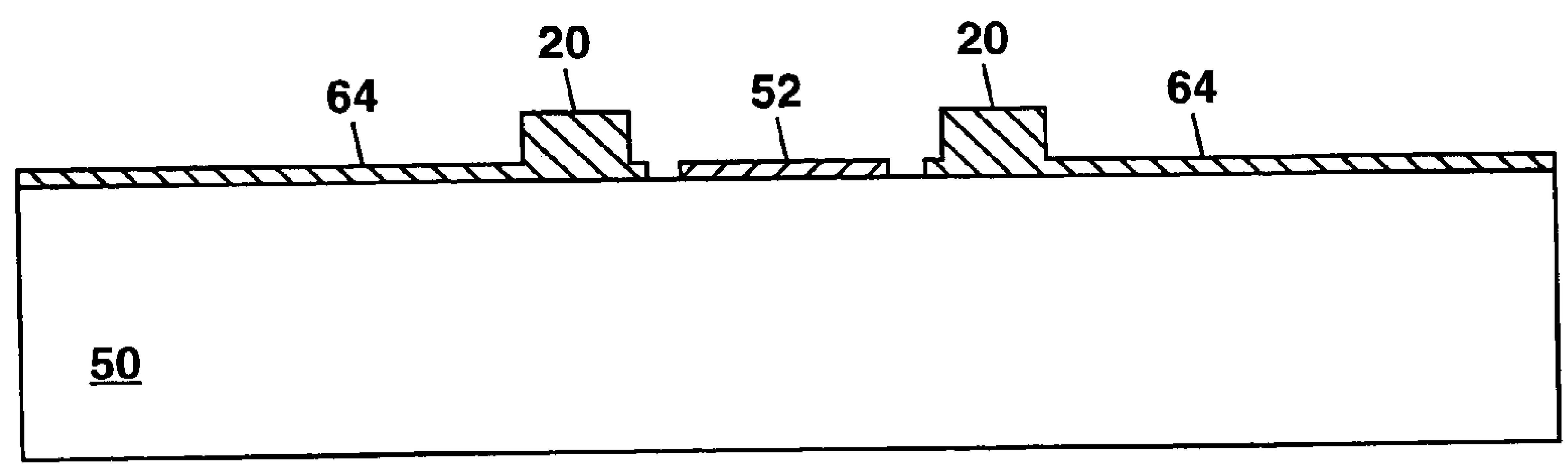

FIG. 7F

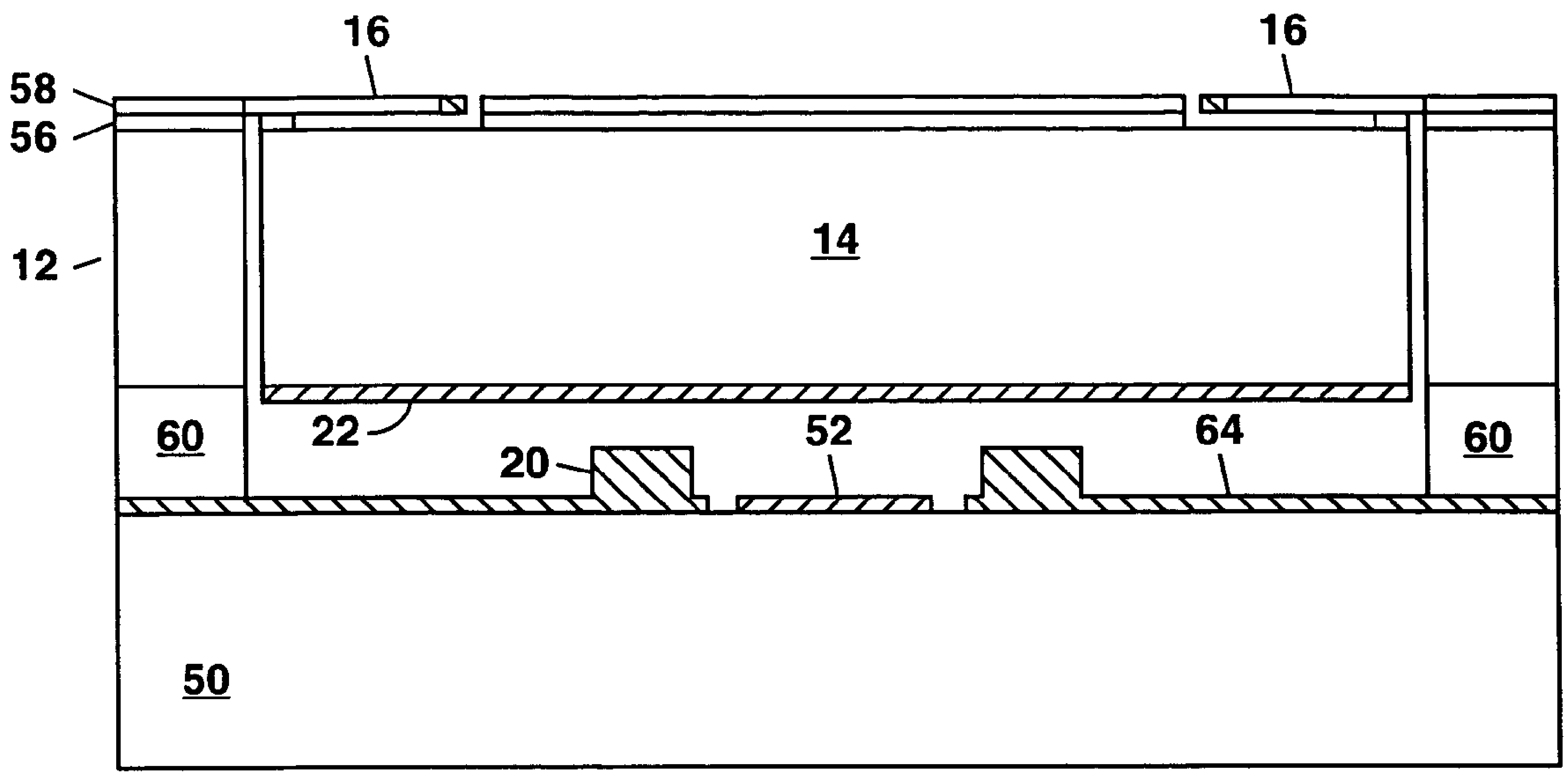

FIG. 7G

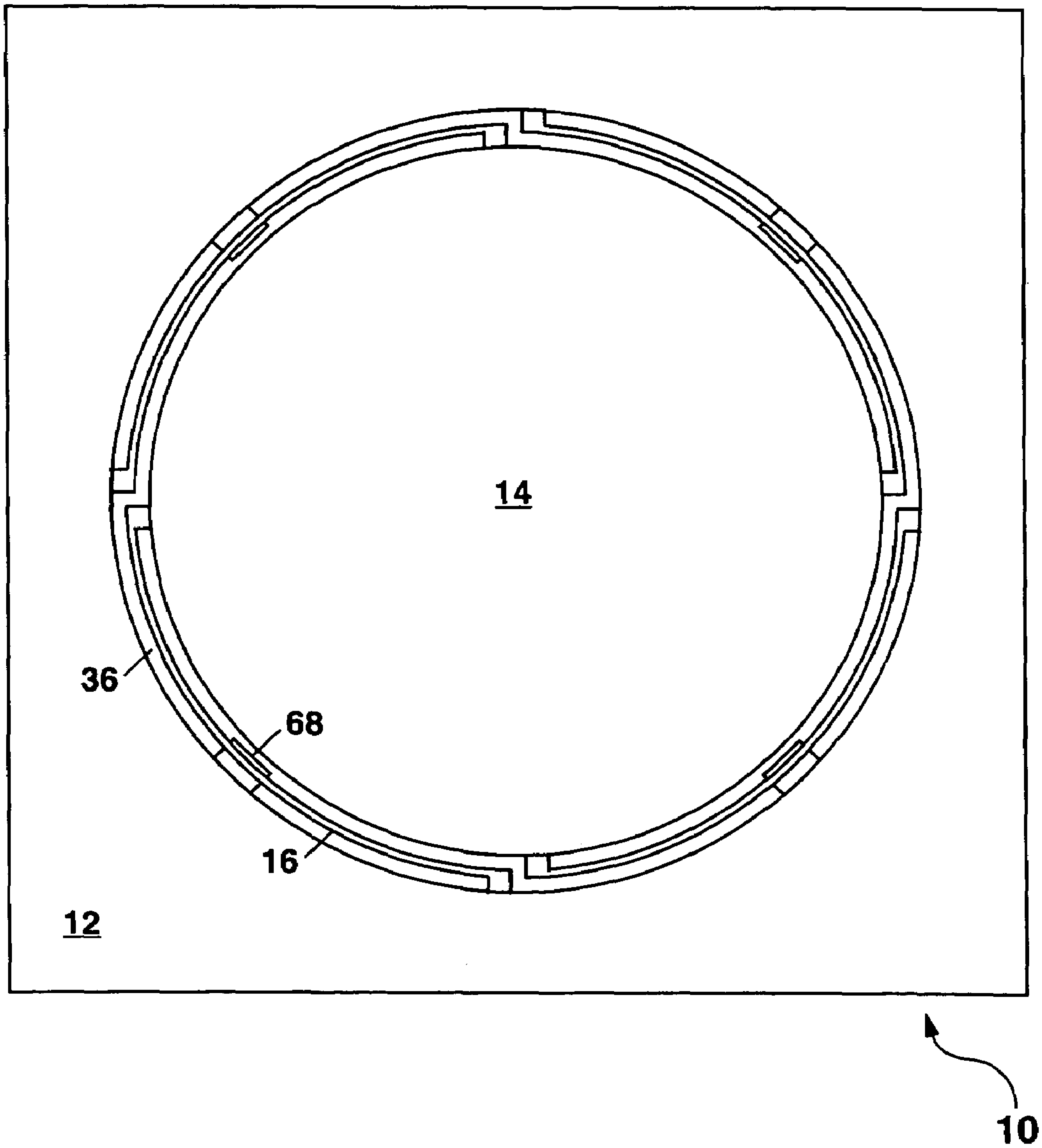

FIG. 8

MICRO ENVIRONMENTAL SENSING DEVICE

GOVERNMENT RIGHTS

This invention was made with Government support under Contract No. DE-AC04-94AL85000 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates in general to microelectromechanical (MEM) devices, and in particular to a MEM acceleration switch for sensing when a particular level of acceleration or deceleration has occurred.

BACKGROUND OF THE INVENTION

Acceleration switches can be used whenever a particular level of acceleration or deceleration must be sensed. For example, in automobiles, an acceleration switch can be used to sense a crash and trigger the deployment of an airbag, or to sense or a severe braking situation and trigger a seat belt tensioning device.

The present invention represents an advance in the art of acceleration switches by providing an acceleration switch that can be formed by micromachining. This minimizes a need for conventional precision machining and piece-part assembly.

The acceleration switch of the present invention can be formed using batch fabrication techniques, with individual devices having acceleration set points which can be selected over a wide range from 1 G to one thousand G or more, where G is the acceleration due to gravity.

These and other advantages of the present invention will become evident to those skilled in the art.

SUMMARY OF THE INVENTION

The present invention relates to a microelectromechanical (MEM) acceleration switch which comprises a substrate; a proof mass flexibly connected to the substrate by a plurality of folded springs located around a periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular to the substrate in response to a sensed acceleration, and further comprising a first electrode located on a major surface of the proof mass; and a second electrode located proximate to the first electrode to provide an electrical connection thereto upon movement of the first electrode into contact with the second electrode in response to the sensed acceleration. The MEM acceleration switch can further comprise an electrical latch to maintain the electrical connection between the first and second electrodes after the sensed acceleration has occurred.

The substrate and the proof mass can each comprise silicon. Each folded spring can also comprise silicon, which can be either monocrystalline silicon when a silicon-on-insulator substrate is used, or polycrystalline silicon when a silicon substrate is used.

The thickness of the proof mass can be greater than or equal to the thickness of the substrate; and each folded spring can have a thickness in the range of 1–50 microns, for example, with the exact thickness of each spring depending upon a threshold value of the acceleration which is to be sensed by the MEM acceleration switch. The major surface of the proof mass can have a shape that is generally either circular or polygonal. The number of folded springs can comprise, for example, three to sixteen folded springs. Each folded spring can further comprise a first pair of spring arms connected to the proof mass, and a second pair of spring arms connected to the substrate, with the first and second pairs of spring arms being connected together by a cross-beam. One or more stops can be optionally provided on the substrate extending over the periphery of the proof mass to limit movement of the proof mass in a direction away from the second electrode.

The second electrode in the MEM acceleration switch can be located on a submount whereon the substrate is attached, or alternately can comprise a pin of a package whereon the substrate is attached. Yet another electrode (i.e. a third electrode) can be located on the submount or in the package. In this case, the first electrode can contact the second and third electrodes as the proof mass is moved in response to the sensed acceleration and thereby provide an electrical connection (i.e. a switch closure) between the second and third electrodes via the first electrode, or from the first electrode to the second and third electrodes. The first electrode can be electrically connected to the substrate through the proof mass and the plurality of folded springs.

The present invention further relates to a MEM acceleration switch which comprises a substrate; a proof mass flexibly anchored to the substrate by a plurality of folded springs located around a periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular the substrate, and with the proof mass having a metallization covering at least a portion of a major surface thereof; and at least one electrode located proximate to the metallization to form an electrical contact therewith upon movement of the proof mass in response to an acceleration event above a threshold value. An electrical latch can optionally be included in the MEM acceleration switch to maintain the electrical contact after occurrence of the acceleration event.

The substrate and the proof mass can each comprise silicon. The major surface of the proof mass can have a shape that is circular or polygonal. One or more of the electrodes can be located on a submount or package whereon the substrate is attached.

The plurality of folded springs generally comprises three to sixteen folded springs, with each folded spring having a thickness, for example, in the range of 1–50 microns (μm). Each folded spring comprises a first pair of spring arms connected to the proof mass, and a second pair of spring arms connected to the substrate, with the first and second pairs of spring arms being connected together by a cross-beam.

The present invention also relates to a MEM acceleration switch which comprises a substrate; a proof mass formed, at least in part from the substrate, with the proof mass being attached to the substrate by three to sixteen springs located around a periphery of the proof mass, and with the proof mass having a metallization covering a majority of a major surface thereof and forming a first electrode; and a second electrode located beneath the proof mass, with the first and second electrodes being spaced apart when the proof mass is in a rest position, and with the first and second electrodes being electrically connected together when the proof mass is urged into contact with the second electrode in response to an acceleration event directed substantially perpendicular to a plane of the substrate and above a threshold value. The MEM acceleration switch can further comprise an electrical latch to maintain an electrical connection between the first and second electrodes after occurrence of the acceleration event.

The substrate can comprise silicon. Each spring can comprise a folded spring or an arcuate spring, and can have a thickness in the range of 1–50 μm, for example. The proof mass can have a circular or polygonal shape. An optional third electrode can be located beneath the proof mass, with the third electrode being spaced apart from the first and second electrodes when the proof mass is in the rest position, and with the third electrode being electrically connected to the first and second electrodes when the proof mass is urged into contact with the second and third electrodes in response to the acceleration event directed substantially perpendicular to a plane of the substrate and above the threshold value. The second and third electrodes can be located on a submount or package whereon the substrate is attached.

The present invention further relates to a MEM acceleration switch which comprises a substrate; a proof mass formed at least in part from the substrate and attached to the substrate by a plurality of arcuate springs located around a periphery of the proof mass, with the proof mass forming a first electrode; and a second electrode located beneath the proof mass. The first and second electrodes are spaced apart when the proof mass is in a rest position, and are electrically connected together when the proof mass is urged into contact with the second electrode in response to an acceleration event that directed substantially perpendicular to a plane of the substrate and above a threshold value. The MEM acceleration switch can further comprise an electrical latch to maintain an electrical connection between the first and second electrodes after occurrence of the acceleration event. The MEM acceleration switch can also comprise a plurality of lateral stops to limit movement of the proof mass in the plane of the substrate.

Additional advantages and novel features of the invention will become apparent to those skilled in the art upon examination of the following detailed description thereof when considered in conjunction with the accompanying drawings. The advantages of the invention can be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating preferred embodiments of the invention and are not to be construed as limiting the invention. In the drawings:

FIG. **1** shows a schematic plan view of a first example of the MEM acceleration switch of the present invention.

FIGS. **2**A and **2**B show schematic cross-section views of the device of FIG. **1** along the section line **1**—**1** in FIG. **1**, with the device being in a rest position (i.e. an open position) in FIG. **2**A and in an actuated position (i.e. a closed position) in FIG. **2**B.

FIGS. **3**A–**3**I show schematic cross-section views to illustrate fabrication of the device of FIG. **1**.

FIG. **4** shows a schematic plan view of a second example of the MEM acceleration switch of the present invention.

FIG. **5** shows a schematic plan view of a submount used in the device of FIG. **4**.

FIGS. **6**A and **6**B show schematic cross-section views of the device of FIG. **4** along the section line **2**—**2** in FIG. **4**, with the device being in the rest position in FIG. **6**A and in the actuated position in FIG. **6**B.

FIGS. **7**A–**7**G show schematic cross-section views to illustrate fabrication of the device of FIG. **4**.

FIG. **8** shows a schematic plan view of a third example of the MEM acceleration switch of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. **1**, there is shown a schematic plan view of a first example of a microelectromechanical (MEM) acceleration switch **10**. The MEM acceleration switch **10** in FIG. **1** comprises a substrate **12**, with a proof mass **14** being suspended from the substrate **12** by a plurality of folded springs **16** so that the proof mass **14** is flexibly connected (i.e. anchored) to the substrate **12** and can move in a direction that is substantially perpendicular to the substrate **12** (i.e. substantially perpendicular to a plane formed by a major surface of the substrate **12**) in response to a sensed acceleration (also termed herein an acceleration event, or an acceleration component). The term "folded spring" as used herein refers to a spring which comprises a plurality of spring arms arranged in juxtaposition, with each adjacent pair of the spring arms being connected together.

A plurality of stops **18** are also provided on the substrate **12** in the MEM acceleration switch **10** of FIG. **1** to limit movement of the proof mass **14** in an upward direction (i.e. out of the page of FIG. **1**) so that any substantial motion of the proof mass **14** will be in a downward direction (i.e. into the page of FIG. **1**). Such downward motion of the proof mass **14** will occur in response to an upward-directed acceleration component to which the MEM acceleration switch **10** is responsive.

FIGS. **2**A and **2**B show schematic cross-section views of the device **10** of FIG. **1** along the section line **1**—**1** in FIG. **1** to illustrate operation of the MEM acceleration switch **10**. In FIG. **2**A, the device **10** is shown in a rest position without any applied acceleration component. This is the position in which the MEM acceleration switch **10** is fabricated. In the rest position, the proof mass **14** is suspended from the substrate **12** by a plurality of folded springs **16** so that there is no contact between the proof mass **14** and an underlying electrode **20**.

In FIG. **2**B, in response to an upward-directed acceleration component A indicated by the arrow, the proof mass **14** is urged to move in the opposite direction, and will contact the electrode **20** when the acceleration component A exceeds a predetermined threshold value determined by the mass of the proof mass **14** and the stiffness of the springs **16**. In the example of FIGS. **1** and **2**A, **2**B, a metallization **22** is provided on an underside major surface of the proof mass **14** to form an electrode for the proof mass **14** which can be electrically connected through the springs **16** to the substrate **12**. The metallization **22**, which covers a portion and preferably a majority of the underside major surface of the proof mass **14**, can thus form a relatively low-resistance (e.g. less than a few hundred Ohms, and preferably about 50 Ohms) electrical connection between the proof mass **14** and the electrode **20** when the metallization **22** is urged into contact with the electrode **20** in response to a sensed acceleration above the threshold value.

In the example of the MEM acceleration switch **10** shown in FIGS. **1** and **2**A, **2**B, the substrate **12** with suspended proof mass **14** can be attached to a submount or package **24** wherein one or more electrodes **20** are located. The form of attachment can be using a bonding material **26** such as an adhesive (e.g. epoxy) or solder, or alternately by directly bonding the substrate **12** to the submount or package **24** (e.g. using an anodic wafer bonding process or a low-temperature co-fired ceramic packaging process as known to the art). Those skilled in the art will understand that there are many different ways to attach the substrate **12** to a submount or package **24**.

The package **24** can comprise a conventional semiconductor device package such as a TO-5 or TO-18 header which can be sealed with a cover (not shown) to form a hermetically-sealed MEM acceleration switch **10**. Alternately, the package **24** can be a custom-designed package such as a hermetically-sealed low-temperature co-fired ceramic (LTCC) package. Additional electronic circuitry can be optionally included in a package **24** for the MEM acceleration switch **10** either adjacent to the switch **10** or formed on the substrate **12** when the substrate comprises silicon. This circuitry, which can comprise a semiconductor integrated circuit as known to the art, can be used, for example, to condition an electrical signal produced by activation of the switch **10**, or to provide a trigger signal upon a closure of the switch **10** upon sensing a predetermined acceleration event (i.e. an acceleration component A above the threshold level).

Fabrication of the MEM acceleration switch **10** of FIGS. **1** and **2**A, **2**B will now be described with reference to FIGS. **3**A–**3**I. Although the fabrication will be described in terms of micromachining based on semiconductor processing steps including material deposition and etching, those skilled in the art will understand that fabrication of the switch **10** of the present invention can also be performed using LIGA (an acronym based on the first letters for the German words for lithography, electroplating and injection molding).

In FIG. **3**A, a substrate **12** is provided which can be, for example, a monocrystalline silicon substrate. The silicon substrate **12** is preferably doped throughout for electrical conductivity (e.g. to about 10^{18} cm^{-3}).

In FIG. **3**B, a layer of a sacrificial material **28** (e.g. silicon dioxide or a silicate glass such as TEOS which can be deposited from the decomposition of tetraethylortho silicate by low-pressure chemical vapor deposition at about 750° C. and densified by a subsequent high temperature processing step) can be blanket deposited over the silicon substrate **12** and patterned by reactive ion etching. This patterning, done using a photolithographically-defined etch mask which is not shown in FIG. **3**B, removes portions of the sacrificial material **28** to form a mold for a subsequent deposition of one or more layers of polycrystalline silicon (also termed polysilicon) which will be used to form the springs **16** and the stops **18** by surface micromachining.

Those skilled in the art will understand that the references to “patterning” and “patterned” herein refer to a series of process steps which are well-known in the semiconductor device fabrication art including applying a photoresist to the substrate **12**, prebaking the photoresist, aligning the substrate **12** with a photomask, exposing the photoresist through the photomask, developing the photoresist, baking the photoresist, etching away the surfaces not protected by the photoresist, and stripping the protected areas of the photoresist so that further processing can take place. The term “patterning” can further include the formation of a hard mask (e.g. comprising about 500 nanometers of TEOS) overlying a polysilicon or sacrificial material layer in preparation for defining features into the layer by anisotropic dry etching (e.g. reactive ion etching).

In FIG. **3**C, one or more layers of polysilicon **30** can be blanket deposited over the substrate **12** to completely fill in the mold formed by the patterned sacrificial material **28**. The polysilicon **30** can then be planarized by a conventional chemical-mechanical polishing step to provide a planar surface for the polysilicon **30** and the sacrificial material **28** as shown in FIG. **3**C. This polishing step can also be used to precisely control and adjust the thickness of the polysilicon **30** at the locations wherein the folded springs **16** will be formed.

For this example of the present invention, each folded spring **16** comprises two pairs of spring arms, with one pair of spring arms being connected between the proof mass **14** and a crossbeam **32**, and with the other pair of spring arms being connected between the crossbeam **32** and the substrate **12** as shown in FIG. **1**. The polishing step allows the folded springs **16** to be precisely adjusted in thickness to provide a predetermined threshold value of the acceleration needed to activate the MEM acceleration switch **10**. As an example, the thickness of the folded springs **16** in the device **10** of FIG. **1**, can be 3 μm, with each spring arm having a length in the range of 300–500 μm and a width in the range of 10–30 μm. The crossbeam **32** can have the same thickness as the spring arms, and can be 20–50 μm wide and 200–500 μm long.

In FIG. **3**D, another layer of the sacrificial material **28** can be blanket deposited over the substrate and patterned by reactive ion etching to build up the mold for defining the shape of the various elements being formed from the polysilicon **30** including the springs **16**, stops **18** and a pair of supports **34** for attaching each spring **16** to the substrate **12** (see FIG. **1**).

In FIG. **3**E, another layer of the polysilicon **30** can be blanket deposited over the substrate **12** to fill in the mold formed from the sacrificial material **28**, with any of the polysilicon **30** outside of the mold being removed by another polishing step. This process can be repeated, as needed, to build up the complete structure for the springs **16**, stops **18**, and spring supports **34**.

Each layer of polysilicon **30** described above can be deposited at a temperature of about 580° C. using low-pressure chemical vapor deposition (LPCVD). The polysilicon **30** can be doped for electrical conductivity (e.g. with phosphorous) to about the same level as the substrate **12**. This can be done either during deposition of the polysilicon **30**, or subsequently thereto using an ion implantation or thermal diffusion step. Annealing of the polysilicon **30** at a high temperature (e.g. about 1100° C. for a few hours) can be used to remove or reduce any residual stress in the polysilicon **30**.

In FIG. **3**F, once the structure of the springs **16**, spring supports **32** and the stops **18** has been built up by surface micromachining, these elements can be left embedded in the sacrificial material **28**; and processing of a backside of the substrate **12** can be performed to define the proof mass **14** which can be formed from at least partially from the substrate **12** by a deep reactive ion etching (DRIE) step. This DRIE process step can also be used to remove portions of the substrate **12** underneath the springs **16** to provide room for the springs **16** to move downward in response of an acceleration-induced movement of the proof mass **14** (see FIG. **2**B).

The DRIE process is disclosed in detail in U.S. Pat. No. 5,501,893 to Laermer, which is incorporated herein by reference. Briefly, the DRIE process utilizes an iterative Inductively Coupled Plasma (ICP) deposition and etch cycle wherein a polymer etch inhibitor is conformally deposited as a film over the silicon substrate **12** during a deposition cycle and subsequently removed during an etching cycle. The polymer film, which can be formed in a C_4F_8/Ar-based plasma, deposits conformally over a photolithographically patterned photoresist mask (not shown) which is used to protect areas of the backside of the silicon substrate **12** not being etched and over sidewalls of a cavity **36** being etched from the backside of the silicon substrate **12** around the proof mass **14** and underneath each spring **16**. The cavity **36** can be, for example, about 100 μm wide around the proof mass **14** and can be sized to be about 100 μm larger than the lateral dimensions of the springs **16**.

During a subsequent etch cycle using an SF_6/Ar-based plasma, the polymer film is preferentially sputtered from the cavity **36** and from the top of the photoresist mask. This exposes the silicon substrate **12** in the region wherein the cavity **36** is being formed to reactive fluorine atoms from the SF_6/Ar-based plasma with the fluorine atoms then being responsible for etching the exposed portion of the silicon substrate **12**. After the polymer at the bottom of the cavity **46** has been sputtered away and the bottom etched by the reactive fluorine atoms, but before the polymer on the sidewalls of the cavity **36** has been completely removed, the polymer deposition step using the C_4F_8/Ar-based plasma is repeated. This cycle continues until a desired etch depth is reached, which in the present case is completely through the thickness of the substrate **12** to the sacrificial material **28**, or partway through the sacrificial material **28**. Each polymer deposition and etch cycle generally lasts only for a few seconds (e.g. $\leqq 10$ seconds). The net result is that features can be anisotropically etched into or completely through the silicon substrate **12** while maintaining substantially straight sidewalls (i.e. with little or no inward tapering).

The DRIE etching process can be used to form the proof mass **14** with any desired shape for the major surfaces thereof including a circular shape or a polygonal shape. These shapes for the major surfaces produce a proof mass **14** in the form of a cylinder or right polyhedron (i.e. prism), respectively. The proof mass **14** can have lateral dimensions of up to a few millimeters and will generally be about as thick as the substrate **12** (e.g. 400–600 μm) or more with the additional polysilicon **30** and metallization **22**.

After the DRIE process step has been performed, the photoresist mask can be stripped, and the substrate **12** cleaned. The sacrificial material **28** can then be removed as shown in FIG. **3**G. This can be done by immersing the substrate **12** into a selective wet etchant comprising hydrofluoric acid (HF) for up to a few hours to selectively etch away the sacrificial material **28** while not substantially chemically attacking the silicon substrate **12** or the polysilicon **30** used to form the springs **16** and other elements of the MEM acceleration switch **10**.

The metallization **22**, which has an overall thickness of up to a few hundred nanometers, can be deposited over a lower major surface of the proof mass **14** as shown in FIG. **3**H. This can be done either before or after die singulation when a plurality of MEM acceleration switches **10** are batch fabricated on a common substrate **12**. The metallization **22** and the electrode **20** are preferably formed from nonoxidizable metals such as platinum and gold. The use of dissimilar metals for the metallization **22** and electrode **20** is beneficial to prevent adhesion which might otherwise result from contact between the metallization **22** and electrode **20** when a single type of metal (e.g. gold) is used for both. The adhesion of the platinum or gold can be improved by the use of a thin layer of titanium, or alternately a Ti/TiN/Ti adhesion stack which can be, for example, about 120 nanometers thick. The metallization **22** can be deposited over the lower surface of the proof mass **14** by evaporation or sputtering through a shadow mask, with an exact area of the metallization **22** depending upon the size and location of one or more electrodes **20** which must be contacted by the metallization **22** for operation of the MEM acceleration switch **10**.

In FIG. **3**I, the substrate **12** can be attached to a submount or package **24** to complete the MEM acceleration switch **10**. As an example, a conventional semiconductor device header (e.g. a TO-5 or TO-18 header) can be used as a package **24** for the MEM acceleration switch **10**. Such a header **24** is generally formed from metal with one or more electrodes **20** extending through the metal header and electrically isolated by an insulating material **38** (e.g. glass or ceramic) as shown in FIG. **3**I. Each electrode **20** can be optionally rounded slightly as shown in FIG. **3**I. Other types of semiconductor device headers comprising plastic or ceramic can also be used, in which case, an insulating material **38** is not needed for electrical isolation of the electrode(s) **20**.

In FIG. **3**I, the package **24** can include a recessed portion **40** to allow for movement of the proof mass **14**, or alternately a spacer **60** (see FIG. **6**A) can be provided between the substrate **12** and the package **24** to provide a predefined spacing between the metallization **22** and the electrode **20** when the proof mass **14** is in the rest position. This spacing can be, for example, 40 μm and will generally be in the range of 10–200 μm or more.

As described previously, the substrate **12** and the submount or package **24** can be permanently attached together with a bonding material **26** such as an adhesive (e.g. a conductive epoxy) or solder. In other embodiments of the present invention, the substrate **12** can be attached to a submount or package using diffusion bonding, low-temperature co-firing, etc. The form of attachment between the substrate **12** and the submount or package **24** will, in general, depend on the materials used for the substrate **12** and the submount or package **24**, and the magnitude of the acceleration to be sensed, and cost and reliability factors. A lid (not shown) can be provided over the substrate **12** and attached to the substrate **12** or package **24** to form a hermetically-sealed device **10**.

FIG. **4** schematically illustrates in plan view a second example of the MEM acceleration switch **10** of the present invention. In the device **10** of FIG. **4**, a plurality of folded springs **16** are located within an outline of the proof mass **14** to save space. This allows the proof mass **14** to be made larger than would be the case if the springs **16** were located outside the proof mass outline as in FIG. **1** when the size of the substrate **12** is fixed, or alternately allows a smaller size substrate **12** to be used when the size of the proof mass **14** is fixed.

Underlying the substrate **12** in FIG. **4** is a submount **50** which is schematically shown in plan view in FIG. **5**. The submount **50**, which can be the same size as the substrate **12**, includes a pair of electrodes **20**, which upon actuation of the device **10**, electrically contact a metallization **22** located on an underside of the proof mass **14**.

FIGS. **6**A and **6**B are schematic cross section views of the MEM acceleration switch **10** of FIGS. **4** and **5** taken along the section line **2**—**2** in FIG. **4**. FIG. **6**A shows the device **10** in a rest position; and FIG. **6**B shows the device **10** in an actuated position in response to a sensed acceleration component A above the threshold level.

In the rest position in FIG. **6**A, the proof mass **14** is suspended from the substrate **12** by a plurality of folded springs **16** which are spaced around a periphery of the rest mass **14** as shown in FIG. **4**. In FIG. **6**B, the device **10** is actuated by an acceleration component A which results in the proof mass **14** being urged into contact with the electrodes **20** thereby providing a switch closure which can be used to indicate the occurrence of the acceleration component A, and that the acceleration component A is above the threshold value.

It is possible to electrically latch the device **10** of FIG. **4**, or any of the other examples of the MEM electrical switch **10** described herein, in a closed (i.e. actuated) position by providing a latching electrode **52** on the submount **50** or on the package **24** (e.g. by using a metal portion of the package **24** which can be electrically grounded). The latching electrode **52**, which is shown in more detail in FIG. **5**, can act in combination with the metallization **22** on the proof mass **14** to form an electrical latch which provides an electrostatic force of attraction that can maintain the switch **10** in the closed position after occurrence of the acceleration event above the threshold value. This can be done in several ways. For example, a relatively high resistance electrical connection can be made through the springs **16** to the proof mass **14** and metallization **22** to maintain the metallization **22** at a predetermined electrical potential (e.g. ground electrical potential). A different electrical potential can be maintained on the latching electrode **52**. The electrical potentials on the electrode **52** and the metallization **22** can be selected so that an electrostatic force of attraction in the rest position is much smaller than a restoring force provided by the springs **16** so that the proof mass **14** will not be electrostatically moved downward and latched against the electrodes **20** without the occurrence of an acceleration component A of a predetermined magnitude. Once the acceleration component A is sensed by the switch **10** and the proof mass **14** is urged downward thereby, the electrostatic force of attraction, which increases as the inverse square of the distance between the metallization **22** and the latching electrode **52**, will be sufficient to electrically latch the proof mass **14** in the actuated position. This electrical latching is advantageous to reduce any chatter (i.e. contact bounce) in the switch **10** due to a sudden or changing acceleration component A, and is also advantageous to maintain the switch **10** in a closed position when this is needed after the occurrence of the acceleration event.

Another way that latching of the device **10** in FIG. **4** can be performed is by utilizing an electrical potential provided by the electrodes **20** in combination with a different electrical potential on the latching electrode **52**. In this mode of operation, the metallization **22** can be left floating in the rest position, or alternately connected to a ground electrical potential through a relatively high-resistance current path through the springs **16** to the substrate **12** (e.g. by using a lower doping level of for the substrate **12**, springs **16** and proof mass **14**). The latching electrode **52** can also be maintained at ground electrical potential. Once the acceleration component A is sensed and the proof mass **14** and metallization **22** are urged into contact with the electrodes **20**, an electrical potential present on one or both of the electrodes **20** will be electrically connected to the metallization **22**, and this can result in a potential difference between the metallization **22** and the latching electrode **52** which, in turn, can generate the electrostatic force of attraction needed to latch the device **10** in the closed position.

The second example of the MEM acceleration switch **10** in FIG. **4** can be fabricated as described hereinafter with reference to FIGS. **7**A–**7**G.

In FIG. **7**A, the starting point for fabrication of the second example of the MEM acceleration switch of FIG. **4** is a conventional silicon-on-insulator (SOI) substrate **12** which comprises a monocrystalline silicon body **54**, an insulating layer **56** overlying the body **54**, and a monocrystalline silicon layer **58** overlying the insulating layer **56**. The monocrystalline silicon body **54** can be, for example, 400–500 μm thick, with the insulating layer **56** and the monocrystalline silicon layer **58** each being up to a few tens of microns thick (e.g. 1–50 μm). The monocrystalline silicon body **54** and the silicon layer **58** can both be doped for electrical conductivity (e.g. n-type or p-type doped to 10^{15}–10^{18} cm^{-3}), with an exact doping level depending upon a required electrical resistivity for the substrate **12**, springs **16** and proof mass **14**. The insulating layer **56** generally comprises silicon dioxide. The use of a SOI substrate **12** is advantageous in that the springs **16** can be formed without any residual stress, and since fabrication of the MEM acceleration switch **10** can be simplified.

In FIG. **7**B, the monocrystalline silicon layer **58** is patterned to provide a plurality of openings **62** through the layer **58** to the underlying insulating layer **56**. This defines the shape of each spring **16** which will be formed from the layer **58** and also separates a portion of the layer **58** which will form a part of the proof mass **14** from another portion of the layer **58** which will remain a part of the substrate **12**. The patterning of the monocrystalline silicon layer **58** can be performed by reactive ion etching using a photolithographically-defined etch mask which is not shown in FIG. **7**B. Additional openings **62** can be etched through the layer **58** and through the insulating layer **56** and filled with deposited metal or polysilicon to form vias (not shown) for electrically connecting the metallization **22** to the substrate **12**.

In FIG. **7**C, the body **54** of the SOI substrate **12** can be patterned to provide a cavity **36** to define the shape of the proof mass **14** being formed from the substrate **12**. This can be done by etching from a backside of the substrate **12** using a DRIE step as described previously with reference to FIG. **3**F, with the etching being terminated upon reaching the silicon dioxide insulating layer **56**. The cavity **36** can be extended to etch through the body **54** beneath each spring **16**, if desired. However, this is generally not needed since the springs **16** overlie the proof mass **14** and will bend away from the proof mass **14** as the proof mass **14** is moved downward in response to a sensed acceleration. In the event of an upward movement of the proof mass **14**, the springs **16** can act as stops to limit the upward movement. Additional stops **18** can also be optionally formed from the monocrystalline silicon layer **58** during patterning of the layer **58**, with the stops **18** being attached to the substrate **12** and overlying the proof mass **14** as schematically illustrated in FIG. **1**.

In FIG. **7**D, portions of the silicon dioxide insulating layer **56** are removed underneath the springs **16** and at the locations of each cavity **36** to free up the proof mass **14** and the springs **16** for movement. This can be done using a selective wet etchant comprising HF as described previously with reference to FIG. **3**G. Etching of the insulating layer **56** can be timed to completely remove the silicon dioxide underneath the springs **16** and proximate to the cavities **36**, with the insulating layer **56** elsewhere being left largely intact.

In FIG. **7**E, an underside major surface of the proof mass **14** can be metallized. This can be done, for example, by evaporation or sputtering through a shadow mask as previously described with reference to FIG. **3**H, with the metallization **22** comprising platinum or gold. The thickness of the metallization **22** on the underside major surface can be up to a few hundred nanometers thick, and the metallization **22** preferably covers a majority of the surface area of the underside major surface.

In FIG. **7F**, the submount **50** can be metallized to form the electrodes **20** and **52** thereon, and also to form electrical wiring **64** for connecting the electrodes **20** and **52** to contact pads (not shown). The submount **50** can comprise, for example, a ceramic, substrate having a thickness of about 0.5–1 millimeter, with lateral dimensions of the submount **50** being the same or larger than the lateral dimensions of the silicon substrate **12**. A few hundred nanometers thickness of metal (e.g. gold) can be deposited on the submount **50** by evaporation or sputtering to form the electrical wiring **64** and the latching electrode **52**. The electrodes **20** can comprise additional metal which is built up on the submount **50** to a predetermined height (e.g. 60 μm). This can be done, for example, by a coining process whereby a quantity of gold is ball-bonded or bump-bonded onto the electrical wiring **64** at the location where the electrodes **20** are to be formed. The bonded gold can then being coined (i.e. stamped or molded) into shape to provide a precise height for each electrode **20**. Alternately, the electrodes **20** can be formed by electroplating after providing a mask over the submount **50** with openings at the locations where the electrodes **20** are to be formed. When the metallization **22** comprises gold, the electrodes **20** or the metallization **22** can be optionally coated with a layer of TiN on the order of 100 nanometers thick to mitigate any gold—gold microwelding upon contacting of the metallization **22** with the electrodes **20**.

In FIG. **7G**, the substrate **12** can be attached to the submount **50** using an intervening spacer **60** which can comprise an electrically-insulating material such as a ceramic. The spacer **60** preferably has a thickness which provides a predetermined spacing between the metallization **22** and the electrodes **20**. This spacing can be, for example, in the range of 20–200 μm. An opening **66** is provided through the spacer **60** centered about the proof mass **14** to allow for movement of the proof mass **14**. The opening **66** can be formed, for example, by laser machining. The substrate **12**, spacer **60** and submount **50** can all be permanently bonded together to form the completed MEM acceleration switch **10** which can be packaged in a hermetically-sealed conventional semiconductor header package, or in a low-temperature co-fired ceramic (LTCC) package. Bonding of the substrate **12**, spacer **60** and submount **50** can be performed using an adhesive (e.g. epoxy) or by LTCC processing as known to the art. When LTCC processing is used, a ceramic seal ring can be provided to bond a ceramic cover onto the submount **50** to package the MEM acceleration switch **10**.

FIG. **8** schematically illustrates in plan view a third example of a MEM acceleration switch **10** according to the present invention. The device **10** of FIG. **8** utilizes a plurality of arcuate springs **16** to suspend the proof mass **14** from the substrate **12**, with each spring **16** being attached at one end thereof to the substrate **12** and at the other end thereof to the proof mass **14**. The arcuate springs **16** are preferably made much stiffer in a lateral direction in the plane of the substrate **12** than in a vertical direction perpendicular to the plane of the substrate **12**. The stiffness of the arcuate springs **16** in the lateral direction, however, is much smaller than that of the devices of FIGS. **1** and **4** which utilize folded springs **16**. A very large acceleration component (e.g. due to shock) in the devices of FIGS. **1** and **4** can lead to a buckling (i.e. breaking) of the folded springs **16**; whereas the arcuate springs **16** in the example of FIG. **8** are able to bend laterally so that they are much less susceptible to breaking. This in-plane movement allowed by the arcuate springs **16** in the example of FIG. **8** will not result in actuation of the MEM acceleration switch **10**, but is merely provided to mitigate the possibility for breakage of the springs **16**. A plurality of lateral stops **68** can also be provided in the device **10** of FIG. **8** to limit an extent of the lateral movement of the proof mass **14** so that the proof mass **14** does not bang against the arcuate springs **16** when a large lateral acceleration component is experienced. The lateral stops **68** can extend outward from a sidewall of the cavity **36** as shown in FIG. **8**, with the lateral stops **68** being formed during one or more DRIE steps used to form the cavity **36** so that the lateral stops **68** extend partway or entirely through the thickness of the monocrystalline silicon body **54**.

The device **10** of FIG. **8** can be fabricated as previously described with reference to FIGS. **3A–3I** with the springs **16** being formed of polysilicon, or as previously described with reference to FIGS. **7A–7G** with the springs **16** being formed of monocrystalline silicon. Operation of this example of the MEM acceleration switch **10** is similar to that described previously for the first and second examples of the switch **10**, with the proof mass **14** being urged downward in response to an acceleration component A of a predetermined magnitude in a direction substantially perpendicular to the plane of the substrate **12**. When the acceleration exceeds a predetermined threshold value, a metallization **22** located on an underside of the proof mass **14** will contact one or more electrodes **20** and result in a switch closure.

The matter set forth in the foregoing description and accompanying drawings is offered by way of illustration only and not as a limitation. The actual scope of the invention is intended to be defined in the following claims when viewed in their proper perspective based on the prior art.

What is claimed is:

1. A microelectromechanical (MEM) acceleration switch, comprising:
- (a) a substrate;
- (b) a proof mass flexibly connected to the substrate by a plurality of folded springs located around an outer periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular to the substrate in response to a sensed acceleration, and further comprising a first electrode located on a major surface of the proof mass; and
- (c) a second electrode located proximate to the first electrode to provide an electrical connection thereto upon movement of the first electrode into contact with the second electrode in response to the sensed acceleration.

2. The MEM acceleration switch of claim **1** wherein the substrate comprises silicon.

3. The MEM acceleration switch of claim **2** wherein the proof mass comprises silicon.

4. The MEM acceleration switch of claim **3** wherein each folded spring comprises monocrystalline silicon.

5. The MEM acceleration switch of claim **3** wherein each folded spring comprises polycrystalline silicon.

6. The MEM acceleration switch of claim **1** wherein the proof mass has a thickness equal to or greater than the thickness of the substrate.

7. The MEM acceleration switch of claim **1** wherein the major surface of the proof mass has a shape that is circular or polygonal.

8. The MEM acceleration switch of claim **1** wherein the plurality of folded springs comprises three to sixteen folded springs.

9. The MEM acceleration switch of claim **1** wherein each folded spring comprises a first pair of spring arms connected to the proof mass, and a second pair of spring arms connected to the substrate, with the first and second pairs of spring arms being connected together by a crossbeam.

10. The MEM acceleration switch of claim 1 wherein each folded spring in the plurality of folded springs has a thickness in the range of 1–50 microns.

11. The MEM acceleration switch of claim 1 wherein the first electrode is electrically connected to the substrate through the proof mass and the plurality of folded springs.

12. The MEM acceleration switch of claim 1 further comprising at least one stop on the substrate extending over the periphery of the proof mass to limit movement of the proof mass in a direction away from the second electrode.

13. The MEM acceleration switch of claim 1 further comprising an electrical latch to maintain the electrical connection between the first and second electrodes after the sensed acceleration has occurred.

14. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass flexibly connected to the substrate by a plurality of folded springs located around a periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular to the substrate in response to a sensed acceleration, and further comprising a first electrode located on a major surface of the proof mass; and

(c) a second electrode located on a submount whereon the substrate is attached with the second electrode being proximate to the first electrode to provide an electrical connection thereto upon movement of the first electrode into contact with the second electrode in response to the sensed acceleration.

15. The MEM acceleration switch of claim 14 further comprising a third electrode located on the submount, with the first electrode upon contact with the second and third electrodes providing an electrical connection between the second and third electrodes.

16. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass flexibly connected to the substrate by a plurality of folded springs located around a periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular to the substrate in response to a sensed acceleration, and further comprising a first electrode located on a major surface of the proof mass; and

(c) a second electrode comprising a pin of a package whereon the substrate is attached with the second electrode being located proximate to the first electrode to provide an electrical connection thereto upon movement of the first electrode into contact with the second electrode in response to the sensed acceleration.

17. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass flexibly anchored to the substrate by a plurality of folded springs located around an outer periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular the substrate, and with the proof mass having a metallization covering at least a portion of a major surface thereof; and

(c) at least one electrode located proximate to the metallization to form an electrical contact therewith upon movement of the proof mass in response to an acceleration event above a threshold value.

18. The MEM acceleration switch of claim 17 wherein the substrate and the proof mass each comprise silicon.

19. The MEM acceleration switch of claim 17 wherein the major surface of the proof mass has a shape that is circular or polygonal.

20. The MEM acceleration switch of claim 17 wherein the plurality of folded springs comprises three to sixteen folded springs.

21. The MEM acceleration switch of claim 17 wherein each folded spring comprises a first pair of spring arms connected to the proof mass, and a second pair of spring arms connected to the substrate, with the first and second pairs of spring arms being connected together by a crossbeam.

22. The MEM acceleration switch of claim 17 wherein each folded spring in the plurality of folded springs has a thickness in the range of 1–50 microns.

23. The MEM acceleration switch of claim 17 further comprising an electrical latch to maintain the electrical contact after occurrence of the acceleration event.

24. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass flexibly anchored to the substrate by a plurality of folded springs located around a periphery of the proof mass, with the proof mass being moveable in a direction substantially perpendicular the substrate, and with the proof mass having a metallization covering at least a portion of a major surface thereof; and

(c) at least one electrode located on a submount or package whereon the substrate is attached with the at least one electrode being located proximate to the metallization to form an electrical contact therewith upon movement of the proof mass in response to an acceleration event above a threshold value.

25. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass formed, at least in part from the substrate, with the proof mass being attached to the substrate by three to sixteen springs located around an outer periphery of the proof mass, and with the proof mass having a metallization covering a majority of a major surface thereof and forming a first electrode; and

(c) a second electrode located beneath the proof mass, with the first and second electrodes being spaced apart when the proof mass is in a rest position, and with the first and second electrodes being electrically connected together when the proof mass is urged into contact with the second electrode in response to an acceleration event directed substantially perpendicular to a plane of the substrate and above a threshold value.

26. The MEM acceleration switch of claim 25 further comprising a third electrode located beneath the proof mass, with the third electrode being spaced apart from the first and second electrodes when the proof mass is in the rest position, and with the third electrode being electrically connected to the first and second electrodes when the proof mass is urged into contact with the second and third electrodes in response to the acceleration event directed substantially perpendicular to a plane of the substrate and above the threshold value.

27. The MEM acceleration switch of claim 26 wherein the second and third electrodes are located on a submount or package whereon the substrate is attached.

28. The MEM acceleration switch of claim 25 wherein the substrate comprises silicon.

29. The MEM acceleration switch of claim **25** wherein each spring comprises a folded spring.

30. The MEM acceleration switch of claim **25** wherein each spring comprises an arcuate spring.

31. The MEM acceleration switch of claim **25** wherein each spring has a thickness in the range of 1–50 microns.

32. The MEM acceleration switch of claim **25** further comprising an electrical latch to maintain an electrical connection between the first and second electrodes after occurrence of the acceleration event.

33. A microelectromechanical (MEM) acceleration switch, comprising:

(a) a substrate;

(b) a proof mass formed at least in part from the substrate and attached to the substrate by a plurality of arcuate springs located around an outer periphery of the proof mass, with the proof mass forming a first electrode; and

(c) a second electrode located beneath the proof mass, with the first and second electrodes being spaced apart when the proof mass is in a rest position, and being electrically connected together when the proof mass is urged into contact with the second electrode in response to an acceleration event directed substantially perpendicular to a plane of the substrate and above a threshold value.

34. The MEM acceleration switch of claim **33** further comprising an electrical latch to maintain an electrical connection between the first and second electrodes after occurrence of the acceleration event.

35. The MEM acceleration switch of claim **33** further comprising a plurality of lateral stops to limit movement of the proof mass in the plane of the substrate.

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